

A Review on Non-invasive Blood Glucose Monitoring using RF Sensors

Rahul Krishnan¹, Inam Ullah Khan², Sai Kiran Oruganti³

^{1 2} Lincoln University College, Malaysia; ³ Multimedia University, Cyberjaya, Malaysia
pdf.rahul@lincoln.edu.my

Abstract: Microwave techniques have emerged as a promising alternative to conventional diagnostic and monitoring methods, offering a safe, noninvasive, and user-friendly approach. With advancements in antenna and sensor technologies, microwaves have demonstrated significant potential in healthcare applications, particularly in monitoring glucose levels in critical organs such as the brain, lungs, heart, and bones. This review explores the growing role of microwave-based methodologies in healthcare, highlighting their advantages over traditional techniques. Special emphasis is given to the progress in noninvasive blood glucose monitoring, with a focus on the proven electromagnetic (EM) wave sensing method. Despite substantial progress and increasing global recognition, challenges remain, including the need for viable hardware alternatives to vector network analyzers (VNAs) and improvements in sensor sensitivity and specificity. Addressing these challenges will be crucial for the widespread adoption of microwave-based glucose monitoring technologies in clinical and everyday settings.

Keywords: Microwave; Antenna; Glucose; Detection; Non-invasive.

Introduction

The Developed countries have faced considerable challenges in providing long-term healthcare and wellness services in recent years, largely attributed to increasing costs and an aging population. The World Health Organization (WHO) reported that in 2020, the global population aged 60 years and older was 1.4 billion. It is projected that the population of individuals aged 60 and older will increase substantially, reaching an estimated 2.1 billion by 2050. The population of individuals aged 80 and older is projected to increase threefold during this timeframe, reaching 426 million by 2050 [1][2][3]. The prevalence of diabetes projected for several continents in 2019, 2030 and 2045 are depicted in Figure 1. This demographic shift signifies significant socioeconomic and medical progress, including enhanced life expectancy and improved disease management; however, it presents a considerable challenge to global healthcare systems. The increasing elderly population correlates with a higher prevalence of chronic diseases, disabilities, and age-related conditions, necessitating significant healthcare resources. This trend highlights the necessity for innovative strategies, policies, and methods to enhance resource utilization and address the increasing demand for healthcare services.

In the most recent centuries, the development of diabetes has been directly linked to lifestyles that are deleterious, such as unhealthy diets and insufficient physical activity. This disease has the potential to cause major complications, including kidney failure, blindness, and stroke, if it is not administered in an

appropriate manner. To monitor blood glucose levels, therefore, it is essential to have a technique that is both consistent and dependable. Glucose sensing is categorized into three kinds such as invasive, minimally invasive, and non-invasive as shown in Figure 2. Invasive and minimally invasive cause infections in blood and skin for certain categories of people and maybe mild pain. Most of the devices that are now available demand a blood sample and are deemed to be invasive [4], which causes the patients to experience discomfort. In addition, there are commercial devices that provide a solution for continuous monitoring of blood glucose; however, these devices are quite pricey and normally only survive for about two weeks and are minimally invasive [5]. Consequently, in order to guarantee continuous and convenient monitoring of blood glucose levels, it is vital to have a technology that is more dependable, non-invasive, and inexpensive.

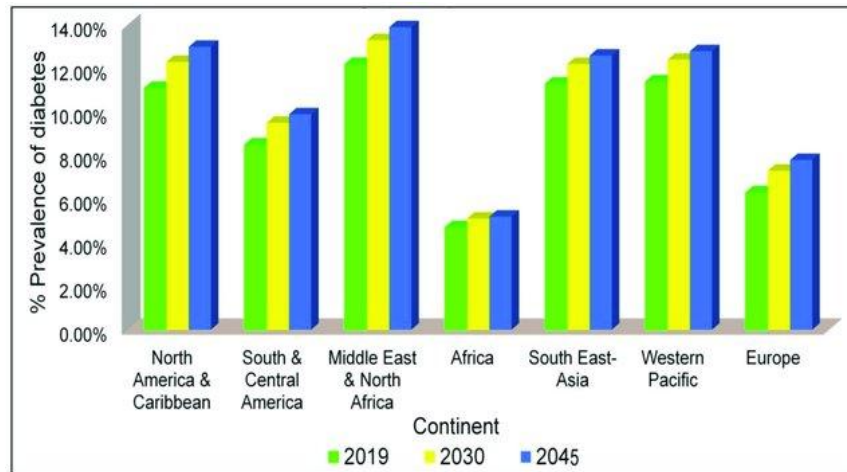


Figure 1. Diabetes prevalence is projected for several continents in 2019, 2030, and 2045 [6]

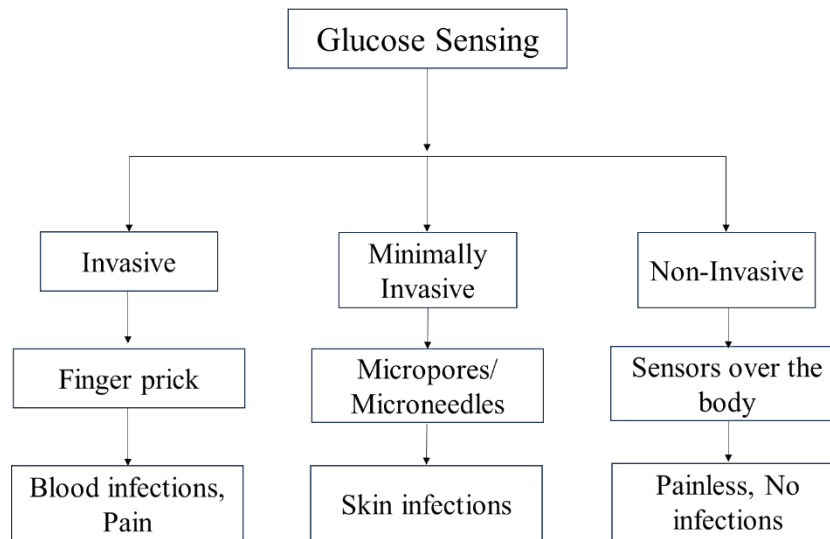


Figure 2. Methods of Glucose sensing

The use of microwaves and radiofrequency waves to measure blood glucose concentrations has seen a rise in popularity over the course of the last twenty years [7]. The dielectric characteristics of a substance govern the behavior of electromagnetic waves within it. Consequently, these features are regarded as

crucial design considerations for the RF/microwave architecture. A substantial body of study has been undertaken regarding the dielectric properties of biological tissues, as documented in references [8]-[11]. To validate the numerical model, a perfect simulation of the dielectric model of blood is required. Recent research papers have been considering various blood phantom models for the effective simulation of the possibility of electromagnetic wave-based glucose detection.

This article provides a comprehensive summary of improvements in noninvasive blood glucose monitoring research over the past decade, focusing on high-frequency electromagnetic (EM) technologies. This section will analyze glucose sensors utilizing electromagnetic waves, which rely on frequency shifts in the radio frequency (RF)/microwave (MW) spectrum induced by variations in glucose concentration. The physical models, wavelength specifications, advantages, and disadvantages of each electromagnetic wave glucose sensing method are elucidated before an examination of the particulars of each technique.

Overview of Electromagnetic Wave Glucose Sensing

An enormous amount of research is going on noninvasive glucose sensing because of its necessity in this current era. Before discussing in depth the various mechanisms used for EM-based sensing, it is vital to understand the wavelength requirement of EM-based sensing, followed by its advantages and disadvantages. Some researchers have gone through various challenges and presented various blood models to simulate and conclude the effectiveness of the detection scheme.

Bandwidth requirement

Since the beginning of the twenty-first century, noninvasive glucose measuring devices have been the focus of extensive research by scientists. A significant number of these procedures are based on spectroscopic techniques, typically looking at the relation between electromagnetic (EM) waves or light and blood glucose. Observations of these interactions can be made using the following three primary mechanisms: absorption, emission, and reflection [12]. The link that exists between the wavelength of an electromagnetic wave and the depth to which it penetrates is an essential component in these measurements. Generally, longer wavelengths can penetrate deeper into tissue and there is a possibility that shorter wavelengths will only permit surface reflection observations.

A Major Concentration on Longer Wavelengths is due to the fact that, deeper tissue penetration is required. The majority of current research has focused on two spectroscopic approaches that make use of longer wavelengths in the optical spectrum. They are (NIRS) stands for near-infrared spectroscopy and impedance Spectroscopy [13]. By gaining access to glucose information from deeper inside the tissue, these approaches have the potential to provide more precise glucose assessments. As a result, they are promising possibilities for noninvasive glucose monitoring.

Advantages

Recent research has focused on impedance, radio frequency, and dielectric methodologies, recognizing their potential for accurate, noninvasive glucose monitoring. Unlike expensive optical spectrometers, EM-wave sensors are made up of standard (PCB) printed circuit boards, potentially reducing costs to very few dollars per unit. This cost-effectiveness, combined with the ability to overcome penetration depth limitations, positions millimeter-wave and lower frequency EM-wave technologies as strong contenders in the quest for affordable, reliable, and user-friendly glucose monitoring solutions.

Challenges

One of the most widely recognized noninvasive method for measuring the glucose level is EM based sensing. But it also exhibit certain challenges in term of the depth of the penetration, placement of sensor, human body movement and sensitivity [14].

Body movement indeed plays a crucial role in the accuracy and reproducibility of non-invasive glucose monitoring techniques. The impact of movement on measurements is a significant challenge that researchers are actively working to overcome. Changes in tissue structure during glucose tests can greatly impact accuracy. The movement can affect tissue dispersion, resulting in erroneous measurements [12]. Ongoing research is focused on developing sensors that are inherently less sensitive to body movements while maintaining high accuracy in glucose measurements by adopting miniaturized sensors to reduce the impact of motion or develop flexible and conformable sensors that move with the body [15].

Blood glucose monitoring relies on sensor sensitivity to accurately measure blood glucose levels. High sensitivity is needed for accurate electromagnetic (EM) sensor readings. Researchers have investigated ways to improve energy concentration and field confinement in the sensing region to increase sensor sensitivity. High energy concentration at the sensing region can improve sensitivity. This method concentrates electromagnetic energy in the glucose sensing area of the sensor. Thus, the sensor can enhance EM field-glucose interaction for more accurate results. Multiple investigations have shown that improved designs and materials improve sensor sensitivity [16] [17].

High field confinement on the sensor is another confirmed principle. This method localizes the electromagnetic field tightly around the sensing area to improve glucose concentration detection. Nanostructures, metamaterials, and plasmonic effects increase field confinement and glucose sensor responsiveness. Researchers have found that sensors using this method can monitor glucose accurately at low concentrations [18] [19]. High energy concentration and high field confinement have been shown to improve EM-based blood glucose sensor sensitivity in practical and theoretical research. Further research in sensor design and materials is projected to improve sensitivity and accuracy, leading to better glucose monitoring systems for diabetics.

Various Blood Models

Researchers have developed numerous models to describe the dielectric properties of human blood for conducting numerical and analytical validation. Several models have been proposed to characterize the dielectric phenomena inside the human body such as Cole-Cole Model, Cole-Davidson Model and Debye Model [20] [21]. The Debye model is a simpler form of dielectric relaxation, often used as a starting point for more complex models. The Cole-Cole model is widely used to describe the dielectric relaxation in biological tissues¹. It extends the Debye model by introducing a parameter α to account for the broadening of the relaxation spectrum.

EM Wave Glucose Sensing Methods

Over the past five years, research on electromagnetic (EM) wave-based sensors for noninvasive glucose monitoring has seen remarkable progress. Many researchers have achieved promising results, successfully quantifying glucose levels through in vitro, in vivo, and ex vivo experiments. Alongside solution-based studies, numerous high-precision clinical trials involving human participants have been conducted. The majority of EM wave-based glucose monitoring systems rely on transmission and/or reflection measurements. As noted earlier, these approaches analyze changes in scattering parameters caused by

glucose concentration variations by examining fluctuations in return loss and frequency shifts associated with resonance.

Freer and Venkataraman [22] explore innovative methodologies for monitoring blood glucose levels without the discomfort associated with traditional invasive techniques. The study investigates the dielectric properties of blood, which are influenced by glucose concentration. By integrating an antenna designed to be placed on the wrist, the researchers simulate how changes in blood glucose levels can shift the resonant frequency of the antenna. These simulations, carried out using a realistic model of human tissue, suggest a potential pathway to develop a reliable, continuous, and non-invasive blood glucose monitoring system. The results shows a good variation between the resonant frequency shifting and corresponding change in glucose levels, offering a promising alternative to current practices that are often cumbersome and uncomfortable for patients, particularly children and adolescents who may struggle with traditional method.

The paper by Mueller et al. [23] presents a comprehensive study on the use of impedance spectroscopy for noninvasive continuous glucose monitoring, addressing the complexities introduced by various perturbing factors that influence skin impedance characteristics. The authors deploy a multisensor glucose monitoring system (MGMS) that incorporates principal component analysis (PCA) to distill relevant physiological information from impedance spectra. They highlight the efficacy of linear least-squares modeling, demonstrating that a personalized modeling approach significantly enhances predictive accuracy for blood glucose levels compared to a global model, with coefficients of determination (R^2) achieving 0.71 versus 0.60, respectively. Moreover, the study emphasizes the need for individual-specific adjustments in models to account for interpersonal variability in skin properties and metabolic responses, thus paving the way for improved noninvasive glucose monitoring methodologies in clinical and everyday scenarios.

Kavitha & Senthil (2019) introduced a novel approach where an antenna is used to detect the diabetes mellitus non-invasively by targeting the pancreas. This study highlights the potential of antenna-based detection in internal organs rather than just blood measurements [23]. Raj et al. (2020) proposed an antenna design for glucose detection. The study incorporated artificial neural networks (ANN) to enhance sensitivity and improve detection accuracy [24]. Islam et al. (2020) compared the performance of UWB antennas and ANN-based methods in glucose level detection. The study demonstrated that ANN-assisted systems could significantly improve measurement accuracy compared to conventional UWB techniques [25]. Jang, Lee, & Yook (2021) developed an RF biosensor for real-time and continuous glucose monitoring. The study emphasized the importance of continuous tracking over periodic measurement for better diabetes management [26].

Deshmukh & Chorage (2021) explored a narrowband microwave sensor for detecting the glucose level, demonstrating its effectiveness in detecting variations in blood glucose levels [27]. Gharbi et al. (2021) introduced an antenna sensor based on textile material for in vitro diabetes diagnostics. The study presented the feasibility of wearable, flexible sensors for real-world applications [28]. Rahayu et al. (2022) designed an antenna that is flexible and used for non-invasive detection of glucose. This research focused on the adaptability of the antenna for wearable applications, improving user convenience [29]. Mahnashi et al. (2023) investigated a microwave-based technique to measure glucose levels in aqueous solutions.

Their findings contributed to refining calibration models for accurate non-invasive glucose monitoring [30]. Syamala et al. (2024) developed a double S-shaped antenna band stop filter for glucose monitoring. The study emphasized the importance of antenna design in enhancing measurement precision [31]. The comparison of various results was superimposed in the below table 1.

Table 1. Comparison of various antenna types, frequency, size and material selection in literature.

Ref	Antenna type	Frequency (GHz)	Dimension (mm ²)	Substrate Materials	Detection Scheme
[23]	U-shaped	1–2.5	-	-	Variation in reflection coefficient due to electromagnetic interaction with glucose solution
[24]	Microstrip antenna	-	-	-	Relates resonant frequency to glucose level using permittivity and conductivity of skin
[25]	CSRR	27.7	36 x 36	RT/Duroid 5880	Electric and Magnetic Fields
[26]	Pyramidal	4.7	60 x 45	FR4	Earlobe + Machine Learning Algorithm
[27]	Spiral	4.69	92 x 5	Glass	Frequency Response
[28]	Microstrip	1.3	68 x 68	RO4003	Frequency Response
[29]	Monopole	2.4	35 x 35	Textile	Return Loss
[30]	Circular patch antenna with CPW feed	2.45	-	Polyethylene terephthalate (PET)	Non-invasive detection of blood glucose using saliva samples
[31]	Double S-shaped	3.21 & 5.66	42 × 16	FR-4 substrate	Frequency shifts based on glucose concentration in a human finger phantom model
[32]	Microstrip antenna	5.7	-	FR-4 substrate	Variation in DC output voltage based on glucose concentration

Conclusions

Microwave-based sensing technologies are currently getting wide recognition in medical diagnostic applications. The possible uses of microwaves in medicine, especially for the monitoring of glucose levels in important organs such the brain, lungs, heart, and bones, are discussed in this paper. Strong rivals to traditional approaches are microwave-based technologies; so, it is projected that in not-too-distant future microwave sensors and related technologies will rule over conventional approaches. Emphasizing the well-established EM-wave sensing technique, the paper also offers a summary of the evolution in noninvasive blood glucose monitoring research. Although noninvasive blood glucose monitoring research is becoming more and more well-known worldwide, additional study is required to solve current obstacles like VNA-substituting technology, sensitivity, and glucose sensor specificity.

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