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Review article

A comprehensive review on electromagnetic wave based non-invasive glucose monitoring in microwave frequencies

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ABSTRACT

Diabetes is a chronic disease that affects millions of humans worldwide. This review article provides an analysis of the recent advancements in non-invasive blood glucose monitoring, detailing methods and techniques, with a special focus on Electromagnetic wave microwave glucose sensors. While optical, thermal, and electromagnetic techniques have been discussed, the primary emphasis is focussed on microwave frequency sensors due to their distinct advantages. Microwave sensors exhibit rapid response times, require minimal user intervention, and hold potential for continuous monitoring, renders them extremely potential for real-world applications. Additionally, their reduced susceptibility to physiological interferences further enhances their appeal. This review critically assesses the performance of microwave glucose sensors by considering factors such as accuracy, sensitivity, specificity, and user comfort. Moreover, it sheds light on the challenges and upcoming directions in the growth of microwave sensors, including the need for reduction and integration with wearable platforms. By concentrating on microwave sensors within the broader context of non-invasive glucose monitoring, this article aims to offer significant enlightenment that may drive further innovation in diabetes care.

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1. Introduction

Diabetes is a widespread health issue impacting individuals on a global scale and is considered a significant public health problem. As a prominent contributor to health disparities, disabilities, and mortality, diabetes is a condition considered by elevated levels of glucose in the blood circulation. The implications of this disease extend beyond individual health, emphasizing the urgent need for comprehensive public health strategies to address its far-reaching impact on communities worldwide [1]. In 2019, approximately 9.3 % of the global population, accounting for 463 million individuals, were affected by diabetes. This figure is anticipated to rise to 10.2 % (578 million) by the year 2030 and further escalate to 10.9 % (700 million) by 2045. Notably, diabetes prevalence exhibits variations based on geographical and economic factors, with urban areas experiencing a higher prevalence at 10.8 % compared to the rural areas at 7.2 %. Additionally, high-income countries report a prevalence of 10.4 %, in contrast to low-income countries where the prevalence is lower at 4.0 %. Alarmingly, half of those diagnosed with diabetes, approximately 50.1 %, are unconscious of their condition. This lack of awareness emphasizes the imperative for heightened public health efforts in diabetes education and screening initiatives [2]. Diabetes encompasses a cluster of metabolic conditions marked by elevated blood sugar levels (hyperglycemia) arising from deficiencies in either insulin secretion, insulin response, or a combination of both factors. The persistent hyperglycemia linked with diabetes is implicated in enduring harm, impairment, and the eventual malfunction of various organs, notably impacting the eyes, kidneys, nerves, heart, and blood vessels. This chronic condition necessitates careful management to mitigate the potential for complications and uphold overall health.

Mostly, diabetes can generally be categorized into two primary types. The first category known as type 1 diabetes in which the primary cause is an absolute deficiency in insulin secretion. Individuals who are at an elevated risk of developing type 1 diabetes often exhibit serological evidence of an autoimmune process affecting the pancreatic islets, and genetic markers may also be indicative of this predisposition. In contrast, the second and more prevalent category is type 2 diabetes. The underlying cause for type 2 diabetes involves a mixture of insulin action resistance and an inadequate compensatory response in insulin secretion. Within this category, there is a notable degree of hyperglycemia, which is significant enough to induce pathological and functional changes in various target tissues. This complex interplay of factors underscores the necessity of comprehensive approaches to both diagnosis and management to address the multifaceted nature of type 2 diabetes [3]. In type 2 diabetes, the body faces challenges in effectively utilizing the insulin it produces [4–6]. Diabetes arises when the pancreas faces challenges in producing an adequate amount of the insulin hormone or when the body encounters difficulties in efficiently utilizing the insulin it naturally produces. Insulin, a hormone generated by the pancreas, plays a crucial role in facilitating the movement of glucose from the bloodstream into the body's cells. However, when the normal operational of this carrier hormone is compromised, as observed in diabetes, there is an elevation in the blood glucose levels, leading to a metabolic disorder known as diabetes mellitus. In this condition, the usual regulatory mechanisms for glucose transport are disrupted, emphasizing the significance of maintaining insulin function for proper metabolic balance [7]. The meticulous monitoring of blood glucose levels enables individuals with diabetes to make well-informed choices concerning their daily routines, dietary choices, and medication adherence. Regular monitoring is vital not just for upholding peak health but also for preventing or minimizing the detrimental consequences that may occur from uncontrolled diabetes like chance of hypoglycemia, hyperglycemia, and glycemic variability (GV) [8]. The rise of Type 2 diabetes has been quickly increasing in recent decades, linked to lifestyle changes like unhealthy diets and limited physical activity. By 2014, the worldwide occurrence among individuals aged 18 and older reached 8.5 %, up from 4.7 % in 1980 [9]. Diabetes, a chronic condition, requires careful management to avoid adverse outcomes such as blindness, kidney failure, stroke, and heart disease [10]. In the beginning of non-invasive research, researchers have investigated numerous methods to check glucose levels in the human body without taking the blood out. Some methods like looking at sweat, pee [11], tears (like in Ref. [12]), and spit. They've also tried breath analysis, connecting blood sugar to acetone made during ketosis [13–16], and different ways of using light to measure, but these haven't been very successful so far [4,17,18]. Also, not many of these methods are effective in keeping track all the time (especially the ones needing spit, pee, and breath samples), but they might still be good for checking and setting up other wearable sensors. Later, researchers moved on to develop radio frequency and electromagnetic wave (EM) wave-based sensors that can operate in the low radio frequencies to high microwave frequencies i.e. from few MHz to 60 GHz. Most of the researchers targeted frequency ranges from 600 MHz to 12 GHz mainly because this frequency range provided better results in terms of glucose sensing. Some researchers have gone for other frequency ranges also such as from mm-wave frequencies (30 GHz–60 GHz) but are less effective since losses increase and are difficult to control. The main parameters that need focus while performing glucose sensing are S-parameters i.e. scattering parameters such as reflection coefficients, transmission coefficients, phase measurements. These parameters help us to analyze changes in effective permittivity that further provides us sensing parameter results to check sensitivity, specificity and detection limits. Current methods of blood glucose monitoring involve ambulatory devices that draw blood with a lancet and measure glucose levels on a chemically treated strip, but they suffer from error rates of up to 20 % [19,20]. Continuous monitoring systems, though less invasive, have practical obstacles, prompting the search for new, reliable, and non-intrusive technologies. For this reason, the non-invasive technique come into play in which most of the researchers have been exploring radio frequency (RF)/microwave sensing method, leveraging wireless technologies and studying electromagnetic waves' interaction with glucose molecules. The main objective of this method and research is to tackle various issues related to the non-invasive monitoring. It mainly focusses on enhancing the sensitivity and improving the selectivity. This review paper deeply explores the characteristics of human tissues that are dependent on glucose, examines the selection of frequencies, and reviews the resonators and antennas utilized in existing literature. The pointing aim is to investigate potential solutions for enhancing sensitivity and selectivity, crucial aspects for the success of non-invasive glucose sensing. For main methods in the non-invasive sensing using RF microwaves, many researchers in the past have focused on different kinds of particular designs that should be new and can help in increasing the performance. The main innovations include the proposal of metamaterial-based sensors, defected ground structures, spoof surface plasmon based sensor designs, sensor designs that are based on particular wave forms (such as sinusoidal wave shapes, etc). These sensor designs should follow some specific principles in order to explain the phenomenon correctly. The main principle innovations also include some sensor designs that are based on some specific principles such as Young's double slit methods, travelling wave, highly concentrated energy principle, highly confined field principle, etc. Most of the reviewed articles in this review paper have mainly followed the above-mentioned design methodologies, principles and innovations that will be discussed in more detail in the next sections with specific references.

1.1. Blood glucose monitoring techniques

Blood glucose sensing methods are primarily categorized into two main types for blood glucose level examination: invasive methods and non-invasive methods. These advancements are crucial in effectively managing diabetes, allowing individuals to monitor their blood glucose levels for effective disease management. Here we will discuss only two main types.

a. Invasive Blood Glucose Monitoring:

Currently, the predominant approach for blood glucose detection involves an invasive method that is widely utilized for its ease of use and utility. This method is commonly utilized in both hospital settings and household glucometers, where blood samples are initially obtained, followed by in vitro analysis to measure blood glucose levels. In hospitals, people typically provide fasting blood samples in the morning, and the blood glucose level is accurately determined utilizing automated biochemical analysers. While this method yields precise results crucial for diabetes diagnosis, its drawbacks include a cumbersome process, prolonged detection time, and the extraction of a significant amount of venous blood. As a result, it is unsuitable for continuous surveillance of diabetic individuals.

Invasive methods involve penetrating the skin to get a blood sample for glucose measurement. Traditional methods such as fingerstick testing and continuous glucose monitoring (CGM) fall under this category. Fingerstick testing is a commonly employed method wherein a small sample of blood is acquired through puncturing the fingertip with a lancet. The typical breadth of a human index finger measures around 14 mm, encompassing various components such as the bone (approximately 6 mm), tissue, dermis (about 3 mm), epidermis (around 1.5 mm), and the nail plate (roughly 1 mm) [21]. CGM, on the other hand, uses a small sensor with sharp needle on it placed under the skin which is continuously in the direct contact with the blood to continuously assess glucose levels in the tissue fluid.

Using needles for blood collection, whether through invasive or minimally invasive procedures, can lead to various discomforts such as pain, numbness, or even a shocking sensation. It's quite common for individuals to experience itching or burning at the spot where blood is drawn. This can be especially traumatic for children, Individuals with cognitive impairments, and those who suffer from needle phobia, affecting around 10 % of the global population [22]. Additionally, when it comes to implantable systems for continuous monitoring, there's often a need for attaching wires to the patient's body to transmit signals, adding another layer of complexity to these medical processes. Invasive methods may cause discomfort and pose infection risks, as they involve the implantation of sensors beneath the skin or the collection of tissue fluids [23,24]. Prioritizing miniaturization and safety is crucial to prevent potential severe injuries to the body [25–38].

b. Non-invasive blood glucose monitoring:

Non-invasive methods provide a more comfortable and user-friendly experience by skipping the need for poking the skin. Instead of extracting blood, these methods utilize sensors technologies to measure glucose levels. Some examples of these non-invasive approaches include microwave sensors and thermal imaging. Non-invasive monitoring of blood glucose entails the measurement of glucose levels in the human bloodstream with not any harm to the underlying tissues. Various techniques exist for non-invasive glucose measurements, that can be broadly categorized into optical, electrochemical, and microwave approaches. Optical approaches encompass a range of techniques such as Infrared (IR) Spectroscopy, polarized optical rotation, Raman spectroscopy, fluorescence, and optical coherence tomography (OCT). It is worth noting that glucose is not only present in blood but also in additional biofluids like spit, tears, sweat, and interstitial fluid. In the electrochemical method, the relationship between biofluids and blood glucose levels is exploited, with the glucose content in body fluids being measured initially. Following this, the blood glucose rate is circuitously derived through the standardization of the system or data model [39,40].

The closest glucose concentration to blood glucose is found in ISF, thereby making it a promising avenue for ISF glucose sensor development. However, numerous studies have indicated the time delay observed between interstitial fluid glucose and blood glucose levels. This time delay ranges from approximately 4 to 10 min [41–44]. Transdermal biofluid extraction commonly employs reverse iontophoresis (RI) technology to swiftly extract ISF, permitting for the rapid assessment of glucose levels.

The concept of non-invasive glucose monitoring was introduced over 20–30 years ago, aiming to alleviate the risks associated with invasive methods such as infection and potential injury to finger tissues. Despite its inception decades ago, it is noteworthy that many non-invasive approaches are still in their nascent stages of development. The literature is replete with numerous descriptions of non-invasive technologies, and recent research has yielded an expanding volume of data. Staying abreast of the present situation in this field necessitates continuous updates. Conducting an online search reveals a wealth of information on the topic, including comprehensive overviews of non-invasive technology [45], future developments in diabetes meters and monitors, and insights into research centres actively involved in advancing this technique [46]. However, given the expansive scope of non-invasive devices, it becomes apparent that no single source can adequately keep pace with the breadth and depth of developments. Among all non-invasive techniques, microwave sensors have been found the most effective due to their advantages over other in terms of simple design, provides flexibility in fabrication, low cost (that is also important), robustness for reuse, good results in terms of high sensitivity, and can be easily integrated to the system level such as wearable platforms. Other advantages of microwaves over others includes their capability to penetrate tissues more effectively and provide real time glucose measurements. These play a vital role in non-invasive monitoring and offer a competitive solution and alternative to standard blood glucose testing techniques. The further sections discuss this in more detail.

1.2. Need for non-invasive technique

People want medical tests that don't involve cutting or poking the body because they want patients to feel more comfortable and avoid the risk of infections or hurting their tissues. These non-invasive methods are friendlier for patients, making it easier for them to follow health check-up routines. It helps everyone, especially kids and older people, to get the tests they need. These methods also make it possible to check health continuously and work with things like smartwatches to understand health better. Using these simpler and safer methods in healthcare is a big change for the better, focusing more on what's good for the patients.

While there exists a myriad of non-invasive glucose sensors, including optical sensors like Near-Infrared Spectroscopy (NIRS) and Raman Spectroscopy, electrochemical sensors like Electrochemical Impedance Spectroscopy (EIS), fluorescence sensors like Fluorescence Resonance Energy Transfer (FRET), and various others such as ultrasound-based, infrared, saliva-based, tear-based, and sweat-based sensors, our paper distinctly concentrates on the category of microwave glucose sensors. By delving into continuous-wave and pulsed microwave sensors, we aim to provide a focused exploration of this specific technology's principles, applications, challenges, and recent advancements in the scope of non-invasive glucose monitoring. This targeted approach allows for a more in-depth examination of microwave sensors and their potential contributions to the field of diabetes management. Non-invasive glucose sensors employ various technologies to measure blood glucose concentration without the need for traditional blood sampling.

1.3. Techniques in non-invasive blood glucose sensors

1.3.1. Near-infrared spectroscopy (NIRS)

It utilizes the absorption characteristics of near-infrared light to estimate glucose concentrations in the blood. Considered highly effective, NIR Spectroscopy is a technique that entails irradiating the skin with light within the wavelength range of 750 nm to 2.5 μm, like a fingerprint, and measuring the reflected light [47–51]. This method has shown precise results in vivo measurements at 1550 nm [52]. Glucose molecules can absorb light, causing changes in reflected light intensity at specific wavelengths. This variation is utilized to estimate glucose concentration. Due to its affordability, compact design, and deep penetration capability, NIR Spectroscopy is a promising technique and has been selected for diverse devices like WizmiTM, Glucose Tracker Clip, Brolis Sensor Technology, GluControl GC300, HELO Extense, GlucoStation, Sensys GTS, TouchTrackPro, and DioMonTech's range of devices [53–55].

Reflectance refers to the process of illuminating the tissue from an angle, whereas interactance involves utilizing a seal as a compromise. On the other hand, transmittance entails the passage of light over the tissue, traversing from one extreme to the other, like the transmission through a finger [49,56]. The research is primarily concentrated on the utilization of reflectance spectra for measuring glucose levels in the inner lip through the employment of NIR Spectroscopy. To determine the level of glucose concentration., Heise and Delbeck [47] utilized a methodology technique, which facilitated the direct measurement of glucose concentration in the tissue, thereby eliminating any dependence on active glucose transportation mechanisms. Additionally, further investigation into NIR is deemed necessary in order to address the diffusion mechanisms. of various compounds inside the tissue, which may have an effect on glucose level measurements. It is also important to acknowledge that NIR is responsive to physiological parameters and environmental variables, for example tissue depth, temperature, skin properties, and surrounding light intensity which can constrain the precision and consistency of measurements [56–58]. For accurate glucose level measurement, the method requires multivariate examination to sufficiently address these diverse attributes [58]. In one study, greater precision was attained employing NIR Spectroscopy alongside SpO2 and heart rate in a compact fingertip sensor [55]. Additionally, research has explored skin and tissue variations to enhance measurement accuracy [53,59]. By employing the Monte Carlo simulation method, a particular study utilized a dual-channel measurement technique to evaluate the levels of glucose and noise signal in relation to diverse skin colures [53]. This research considered the presence of melanin intensity in the skin and examined various optical properties for example the scattering coefficient, absorption coefficient, and index of refraction. The findings revealed that lengthier wavelengths and source detector separations resulted in improved signal-to-noise ratios for individuals with duskier skin tones. However, it should be noted that the ideal wavelength and separations varied for individuals with bright and average skin tones, necessitating specific conditions for both short and long channels.

1.3.2. Raman spectroscopy

It measures the scattering of light to identify molecular vibrations associated with glucose, offering a non-invasive way to quantify levels. Raman scattering is a method in which light scatters, like how X-rays scatter. Imagine shining a laser on something. The molecules in that thing absorb some energy from the laser, vibrate, and then scatter light at different frequencies. This frequency change depends on what the material is made of. Distinct materials exhibit unique vibrational patterns, creating light at particular frequencies. Raman spectroscopy serves as a mean that can figure out what kinds of molecules are present in something [60].

Raman scattering enables quantification of glucose concentration within a substance. Unlike other ways of using light, Raman spectroscopy looks at the basic vibrations of small parts of molecules without too much overlap or confusion. But, measuring glucose this way can be weak because the signal is not very strong, and background noise from the surroundings can make it harder to see the glucose signal [61].

Scientists use some math techniques, like partial least squares regression or support vector regression, to analyze the signals and figure out how much glucose is present. To make the measurements more accurate, some researchers focus the laser on blood vessels in the skin. They use the height ratio of certain peaks in the Raman spectrum to calculate blood glucose levels. In tests with mice, this method displayed a close relationship between Raman intensity and blood glucose, with a small error [62].

Other researchers, like Tang et al. use a special microscope to assess glucose levels within a specimen in more detailed way. They apply math methods to get accurate results, showing a strong correlation between predicted and actual glucose levels [60].

In a recent study, scientists, like Yang et al. found a new way to make Raman signals stronger and more accurate. They used a substance that changes its Raman signals when it binds with glucose. By using special techniques, they could amplify the weak signals and continuously measure glucose levels quickly within a normal range in experiments with rabbit eyes, showing good accuracy [61].

1.3.3. Ultrasound-based sensors

These measures changes in ultrasound waves as they propagate through tissues, providing information about glucose concentration variations. The word “ultrasonic” mentions to sounds with frequencies more than approximately 20–21 kHz. When ultrasound techniques are united with optical methods like near-infrared or mid-infrared, it can enhance the accuracy of readings. The primary aim is to optimize the efficiency of existing optical technology by utilizing amplitude-modulated ultrasonic waves for more precise calculation. In the blood medium, the patterns of standing waves generated by ultrasonic waves lead to molecular oscillations and vibrations. The speed of sound passing through tissue can indicate variations in glucose levels, with the propagation velocity increasing as glucose level rises. The quicker the ultrasonic wave travels over tissue, the speedier it propagates, establishing a direct relationship with glucose concentration [63].

The NIRLUS® system, employing near-infrared light ultrasound, underwent evaluation under standard conditions to quantify the concentration of glucose in the bloodstream [64]. In an intravenous glucose tolerance test conducted on 17 subjects, the NIRLUS system demonstrated consistent and accurate results, aligning well with a “gold standard” laboratory reference system. Another method, ultrasound-modulated optical sensing (UOS), Park et al. pioneered the implementation of a method for non-invasively monitoring blood glucose levels [65]. The system utilized an infrared laser and a attentive ultrasonic transducer, exhibiting accurate results and displaying significant potential.

In a distinct study, researchers utilized a 940 nm IR light and a 40 kHz ultrasonic transmitter unit [66]. The study involved mixing human blood plasma with phantom specimen to observe differences induced by glucose. The outcomes of an oral glucose tolerance test showed maximum values in the Fast Fourier analysis for different phases of blood glucose examinations. Another approach involved mid-infrared spectroscopy, demonstrating an ultrasonic standing wave that creates reflection planes below the surface of the sample [67]. The study successfully identified glucose absorbance within an ultrasonic steady wave using an imaging-type Fourier spectrometer and optical consistent tomography.

In summary, the integration of ultrasound and optical techniques holds the potential to enhance the measurement precision of glucose levels, offering non-invasive and precise alternatives to traditional methods.

1.3.4. Fluorescence sensors

This approach utilizes fluorescent agents to identify the presence of glucose molecules in the bloodstream. Various methods are utilized, such as detecting alterations in the transmission of the phenomenon of fluorescence resonance energy transfer involves the transfer of energy between a fluorescent donor and acceptor, while another method involves the observation of alterations in the natural fluorescence of enzymes due to the presence of glucose. A research study pointed out that glucose levels in tears closely resemble those in blood, suggesting the potential use of tear fluorescence as a non-invasive method for monitoring glucose levels. Khalil highlighted that this technique could track blood glucose levels with a delay of approximately 30 min and is not influenced by fluctuations in ambient light levels. Photonic detection is completed employing polymerized crystalline colloidal arrays. These arrays react to diverse concentrations by diffracting visible light [68,69].

Photonic sensing, particularly in fluorescence technology, can encounter challenges due to intense scattering phenomena. Additionally, there are constraints associated with short lifetimes and biocompatibility that require attention, potentially addressed through the implementation of colorimetric assays [70].

1.3.5. Sweat- based sensors

In recent years, there has been a notable emphasis on the advancement of a non-invasive glucose sensor utilizing sweat as a foundation in various research studies. Sweat, A biological secretion generated by sudoriferous glands, contains various components such as metabolic byproducts, ions. Its composition, inclusive of blood-related biomarkers, positions sweat as an appealing substrate for non-invasive surveillance. The configuration of band-style apparatus facilitates wearability and continuous monitoring, offering the potential to integrate drug-delivery modules for achieving continuous monitoring of blood glucose levels combined with smart closed-loop therapy Lee et al. ingeniously developed a wearable device for monitoring glucose in sweat, incorporating a multistage transdermal drug delivery component [71]. The sensor-monitoring component incorporated a blood sugar sensor, pH sensor, heat level sensor, and humidity sensor, contributing significantly to enhanced sensor precision. The detection of glucose content in sweat triggered the multi-phase heating and drug-delivery system module. This, in turn, facilitated the timely and precise release of hypoglycemic drugs Via a transdermal therapeutic approach, achieving non-invasive closed-loop glucose control. This method not merely eradicated the discomfort related with injections but additionally circumvented the gastrointestinal tract, which leads to decreased dosages compared to ingestion by mouth and avoiding digestive system side effects. Despite these advancements, challenges persist in sweat-based glucose sensing, encompassing issues like sweat collection difficulties, fluctuations in the activity of glucose oxidase (GOx) due to lactic acid secretion, fluctuations in environmental temperature, and the potential separation of the enzyme in response due to mechanical rubbing and deformation of the skin.

Zhai et al. introduced a novel wearable glucose sensor employing non-invasive methods utilizing upright gold nanowires resembling enokitake mushrooms. Addressing the impact of varying flexible strains on detection sensitivity, the study revealed a diminishing sensitivity with increasing strain. Detection limits were noted at 25.45, 19.45, 11.79, and 4.55 $\mu AmM^{-1}cm^{-2}$ for strains of 0, 10 %, 20 %, and 30 %, respectively [72]. The findings underscored that heightened strain led to reduced sensitivity, ultimately reaching a recognition limit of 10 μM.

The non-invasive glucose sensor utilizing sweat offers several advantages, including the ease of sweat sampling and the integration of highly wearable devices capable of continuous measurement, ensuring comfort for the user. However, a notable limitation is that sweat can exclusively be assessed upon reaching the skin's surface, presenting a unique challenge in collecting sweat effectively immediately and in moderate amounts. Current methods for sweat extraction involve long and intense physical activity, warming, pressure, and ionization enthalpy excitation, each with its own drawbacks. Those diagnosed with diabetes may find prolonged exercise unsuitable for inducing sweating while heating and ionization stimulation can lead to discomfort and pain.

Furthermore, the relatively lower responsiveness attributed to the reduced glucose content in sweat, coupled with a specific hysteresis related to blood glucose level, remains a significant hindrance to its widespread application [73–75].

1.3.6. Electromagnetic sensing

Much like bioimpedance spectroscopy, this technological approach examines the dielectric parameters of blood. The primary distinction lies in the methodology: bioimpedance spectroscopy employs an electric current, while electromagnetic sensing relies on the electromagnetic coupling between two inductors [76,77]. In this sensing approach, electric currents are employed to detect variations in the dielectric parameters of blood, Fluctuations in glucose intensity may suggest potential shifts in glucose conc [78]. The frequency range typically utilized for this technique spans 2.4–2.9 MHz. However, the most effective frequency for maximizing sensitivity to glucose changes depends on the temp. of the examined average. Identifying this ideal frequency is critical for optimizing the device's performance.

For example, Gourzi et al. recommended that the most effective frequency is 2.66 MHz at 24 °C [76]. In Ref. [76] author report on non-invasive blood glucose measurements using calf blood. Our method utilizes an electromagnetic sensor based on eddy currents, detecting glucose levels by monitoring changes in dielectric properties. We conducted measurements under static and dynamic conditions, simulating blood circulation. Results show that even under challenging circumstances, we can detect glucose level changes of approximately ± 2 g/l, offering promising insights for non-invasive glucose monitoring. In contrast, an additional investigation, using blood of pig, proposed that the most effective operational frequency is 7.769 GHz at 25 °C [79]. This discrepancy highlights the necessity of determining the ideal frequency to enhance sensitivity to glucose variations under different conditions. In Ref. [79] researchers developed a novel electromagnetic resonant spiral sensor to measure glucose levels in pig blood and liquid solutions. By utilizing real-time electromagnetic interactions, we achieved a resolution of 5 mg/dL within the 100–600 mg/dL range. Operating at around 7.65 GHz for glucose solutions and 7.77 GHz for pig blood, variations in glucose concentration alter the microwave reflection coefficient. Our system boasts a signal-to-noise ratio of approximately 34 dB and a minimum detectable signal level of 0.022 dB/(mg/dl). This non-invasive, contactless method could revolutionize glucose monitoring as a bloodless glucometer.

1.3.7. Bioimpedance spectroscopy (BS)

Dielectric impedance spectroscopy, also referred as Bioelectrical Impedance Spectroscopy (BS), evaluates alterations in the permittivity and in the conductivity characteristics of the membrane in resulting from fluctuations in blood glucose levels. This technology based on the fundamental principle that alterations in plasma glucose level drive its functionality led to change in the conc. of potassium and sodium ions, ultimately causing shifts in the conductive properties of the red blood cells membrane [80]. This establishes a direct connection between glucose levels, indicating a clear correlation. and membrane conductivity. In the BS technique, A low-level alternating current with a predetermined intensity is employed to gauge the corresponding resistance. This process allows for the determination of conductivity, reflecting the glucose-induced shifts in the membrane. The simplicity of this method makes it potentially cost-effective and straightforward for practical applications. However, it's essential to consider sensitivity to temperature fluctuations and perspiration when implementing this technique.

One drawback of this technology is its reliance on an equilibration process, necessitating users to rest for a duration of 60 min before initiating measurements [81]. Furthermore, there are unresolved issues, including the impact of temperature and body hydration levels such as skin moisture, sweat, and overall hydration on the accuracy of readings [82].

1.3.8. Dielectric Spectroscopy or impedance spectroscopy

Dielectric Spectroscopy, commonly interchanged with Impedance or Microwave Spectroscopy, is employed to examine the intricate magnetic characteristics of the skin. This is achieved by exposing them to an electric field through various frequencies, permitting the assessment of fluctuations in glucose level and the extraction of data regarding their composition, configuration, and property changes [83,84]. The dielectric characteristics of the neighbouring medium are affected by glucose, a polar molecule. Analysing these properties across various frequencies falling within the microwave spectrum enables the correlation detected variations in glucose levels.

Despite previous unsuccessful attempts with devices, the current development of DeepGluco™ by Alertgy in Melbourne is presently in the process of creating an uninterrupted wearable wrist band (device) that employs Dielectric Spectroscopy for enhanced tissue penetration [83].

Omer, Shaker [85] was the first to develop a cost-effective microwave sensor encompassing a frequency spectrum of 2.4–2.5 GHz, exhibiting encouraging outcomes with enhanced responsiveness in the identification of fluctuations in glucose concentrations. This sensor possesses the capability to enable tailored and meticulous continuous glucose surveillance. The paper [85], presents a novel portable planar microwave sensor for non-invasively monitoring blood glucose levels. Featuring four hexagonal-shaped complementary split ring resonator (CSRR) cells on an FR4 dielectric substrate, the sensor operates in the 2.4–2.5 GHz ISM band. In vitro measurements demonstrate significant frequency-shift responses to glucose concentrations of 70–120 mg/dL. Radar-driven prototypes show distinct patterns in receiving channel data corresponding to glucose level variations, validated using Principal Component Analysis (PCA). The sensor's advantages include compact size, ease of fabrication, cost-effectiveness, non-ionizing nature, and minimal health risks. Initial in-vivo experiments suggest its potential for continuous blood glucose monitoring, paving the way for radar-powered wearable monitors.

Dielectric Spectroscopy is vulnerable to the effects of perspiration, bodily movement, surrounding conditions, moisture in the air, skin temperatures, and the ability to conduct electricity. Therefore, it is imperative to gauging these environmental and physiological factors in order to enhance the precision of the measurements [86]. Additionally, factors such as the amount of water present, concentration of electrolytes, and other elements related to glucose levels can also have an impact on this technique. A significant breakthrough was made by Hanna and Tawk [86], who developed an innovative wearable sensor system that incorporates electromagnetic technology into sock garments. This system utilizes personalized multisensor quasi-antenna arrays and signal processing based on machine learning, facilitating wireless and ongoing tracking of glucose fluctuations in the blood, achieving remarkable precision. The multisensor setup is capable of monitoring motion, skin temperature, external temperature, Skin Conductance Response and humidity.

1.3.9. Microwave sensors

In simple terms, microwave sensors are created considering how microwaves interact with tissues. The way microwaves bounce back, pass through, and get absorbed is closely tied to the tissues' dielectric properties [87,88]. Importantly, the dielectric properties differ according to fluctuations in glucose levels. Research in the field of non-invasive blood glucose measurement centres on the utilization of RF/microwave sensing, with a specific emphasis on the fingertips owing to their abundant blood supply and biological consistency. Nevertheless, the detection of glucose-induced alterations in blood permittivity results in minor frequency shifts in sensors. There are some challenges for non-invasive blood glucose monitoring through the fingertip, ear, and other different parts of the body using microwave sensors. Discrepancies originate from the varying thicknesses of biological layers and the distinctiveness of fingerprints. For ear-based sensors, another challenge is the curved surface that doesn't quite allow the sensor to completely attached. The sensor needs to be flexible and very compact. Also, the sensor needs to eliminate the bending effects that can cause change in results for different measurements. The purpose of the investigation is to inspect the impacts of these factors on measurements taken on the fingertips [89–91]. In Ref. [89], authors proposed Non-invasive glucose monitoring technology is revolutionizing diabetes management, offering a painless, efficient, and cost-effective alternative to traditional methods. This provides an overview of non-invasive and very little-invasive glucose sensing sensors, available gadgets, regulatory standards, and emerging innovations. It explores advancements in signal enhancement algorithms and predicts future trends, including the utilization of diverse electromagnetic spectrum bands. The integration and adoption of these novel technologies are imminent, promising a significant impact on diabetes care. In Ref. [90], research proposed that non-invasive assessment of blood sugar levels using RF/microwave sensing shows promise, particularly at the fingertips due to their rich blood supply and consistent biological layers. This technique relies on detecting changes in blood permittivity with a resonator sensor. However, glucose-induced permittivity changes are small, leading to minimal frequency response shifts. Variations in biological layer thickness and individual fingerprints can affect measurement consistency. This paper investigates the influence of these factors on fingertip glucose measurements. In Ref. [91], authors proposed a model employing Debye relaxation describes the permittivity of glucose solutions up to 40 GHz. The study compares these measurements with invasive blood tests on over 40 specimens. The investigation delves into methods utilizing reflection and transmission for measuring biomedical concentrations. Various sensing structures are subjected to wideband measurements as part of the study, including the use of six-port reflectometers and homodyne vector network analyzers. Yet, we're not certain about the exact spot in the tissue where these changes take place or the particular manner in which the properties of the tissue change and the way in which the dielectric properties shift remains uncertain [92]. The characteristics of the mechanisms by which electrical signals traverse living tissues have been thoroughly documented in various sources [93]. The key to microwave diagnosis lies in contrasting the dielectric characteristics of ordinary and irregular tissues. Recently, in the non-invasive continuous observing of blood glucose, numerous researchers have shown interest in the connection between glucose level in the bloodstream or other bodily fluids and the way these fluids affect microwaves. This interest has sparked additional studies on microwave sensors [94]. In Ref. [94], the work proposed a sensor a novel microwave fluidic glucose sensor that utilizes dual complementary split ring resonators and a switching circuit for non-invasive and continuous glucose concentration detection. The sensor detects subtle changes in the dielectric constant of glucose solutions, enabling accurate measurements. It addresses environmental factors such as surrounding humidity and temperature, ensuring reliable performance under practical conditions. The sensor demonstrates high sensitivity and reproducibility, capable of detecting glucose level from 0 mg/dL to 400 mg/dL.

2. Principles of microwave glucose sensing and based sensors

a. Dielectric Properties of Tissues

The electrical characteristics of biological tissues play a crucial role in microwave detection. The paper explores how alterations in these properties, particularly related to glucose fluctuations, form the basis for glucose concentration measurements.

Dielectric properties describe how a material reacts when subjected to an electric field. When it comes to glucose, it's a polar molecule due to differences in electronegativity between its oxygen and hydrogen atoms. This creates a dipole moment, where one side of the molecule exhibits a minor negative charge, while the opposite side displays a slight positive charge.

When exposed to an electric field, like with microwaves, polar glucose molecules frequently to align with the field. In simpler terms, they try to position themselves to minimize the energy associated with the electric field. This alignment causes the glucose molecules to vibrate or oscillate.

The relative permittivity, also called relative permittivity, measures how well a substance can store electrical energy within electric field. Polar molecules like glucose generally have greater relative permittivity than non-polar substances.

The relative permittivity parameter is highly crucial in the context of microwave glucose sensors. The relationship between the electric field during EM wave propagation and polar glucose molecules brings out the alterations in the dielectric properties of the sample that leads to modifications in the microwave signals. These alterations can be measured and linked the glucose level present in the specimen is referred to as the conc., forming the foundation for non-invasive glucose monitoring.

The attributes of a substance's dielectric properties play a crucial role in shaping the behaviour of waves within that material. Consequently, the dielectric properties of a substance stand out as crucial factors in the design of RF/microwave structures. The evolution initially witnessed in mobile communications, followed by the development of body-centric communication encompassing diverse wearable and implantable gadgets, alongside their possible application for monitoring physiological functions, has sparked considerable interest in understanding how electromagnetic waves are influenced by the human body. This interest extends to areas such as ensuring wellbeing and harmless exposure, sustaining connections between a cellular phone and a Central hub, or continuing connections between the mobile and a Bluetooth headset [95]. To establish a comprehensive record, extensive documentation in the literature has been dedicated to the dielectric properties of tissues, encompassing instances with organic irregularities [96–99].

The efficacy of microwave diagnostics and therapeutic uses depends on variations in dielectric characteristics between healthy and diseased tissues (e.g. Refs. [100,101]). It is essential to assess these characteristics. In recent times, the concept of utilizing microwaves for non-invasive and constant tracking of blood sugar levels has inspired numerous scientists to explore the impact of glucose on dielectric properties in blood and other bodily fluids.

The total volume of blood comprises plasma, RBC, and only few percent white blood cells and platelets, collectively known as buffy coat [102]. Plasma primarily comprises water (approximately 90 %), in addition to containing roughly 6.9 % proteins, 0.49 % inorganic salts, 0.4–0.7 % lipids, 0.07–0.1 % glucose, and less than 0.069 % lactic acid, carbamide, and amino acids [103]. Plasma also carries glucose through the circulatory system from blood arteries to arterioles and the smallest blood vessels. The concentrations of glucose in capillary blood and arterial blood are very similar [104]. Upon reaching the capillaries, glucose disperses into the liquid surrounding tissue cells. It is then transformed into energy, either utilized immediately or stored for future use. Fluctuations in human blood glucose levels have a minor impact on dielectric properties, necessitating a sensor with high sensitivity. Therefore, using a high-accuracy, stable, multi-frequency resonator is crucial to reduce noise effects. Furthermore, employing suitable signal-processing techniques is essential to discern low-amplitude variations amidst significant fluctuations [105–109].

b. Electromagnetic Interaction with Biological Tissues

Microwave sensors operate based on the influence between electromagnetic waves and tissues. The review delves into the fundamental principles governing this interaction, emphasizing the benefits of microwaves, such as their capability to penetrate tissues and provide realistic blood glucose data. Microwave glucose sensors play a vital role in non-invasive glucose monitoring, offering a promising alternative to traditional blood sampling methods for humans with diabetes. The fundamental principle underlying these sensors lies in the electromagnetic interaction between microwaves and biological tissues, particularly the changes in dielectric properties of tissues as a function of glucose conc. When microwaves, typically in the GHz range, interact with biological tissues, they experience a change in their propagation characteristics due to the presence of glucose molecules. This change is mainly ascribed to the polar nature of glucose molecules, which affects the dielectric constant of the neighbouring medium. The dielectric properties of tissues, such as conductivity and permittivity, are sensitive to the glucose concentration. As glucose levels fluctuate, so do the dielectric properties of the tissues being monitored. Microwave sensors exploit this sensitivity to detect and quantify glucose levels without the need for invasive procedures. The sensors typically consist of an antenna that emits microwave signals into the target tissue and another antenna that receives the signals after interaction with the tissue. The variations in the received signals are then analyzed to determine the glucose concentration. These sensors leverage the unique interaction between electromagnetic fields and biological tissues to non-invasively monitor glucose levels, a critical factor for individuals with diabetes. Theoretical and experimental studies, such as those presented in Ref. [110]. This paper explores the interplay between electromagnetic fields and superficial blood vessels in biological tissues to develop a near-field microwave detecting system for non-invasive glucose observation. Numerical simulations highlighted the importance of sensor geometry in generating an enhanced near-field zone. Experimental studies assessed the intricate reflection coefficient from the sensor, showing a correlation between signal magnitudes and glucose concentrations in the frequency span of 4.3–4.6 GHz.

One key aspect of the electromagnetic interaction in these sensors is the penetration depth of microwaves into biological tissues. Microwave signals can penetrate tissues to different depths depending on their frequency. Higher frequency microwaves have shorter wavelengths and penetrate tissues more superficially, making them suitable for monitoring glucose levels in shallow tissues like the skin. On the other hand, lower frequency microwaves can penetrate deeper tissues, allowing for monitoring glucose levels in organs [111]. This research investigates the extent to which microwaves can penetrate various types of biological tissues with different structures, aiming to improve an existing sensor that employs a Complementary Split Ring Resonator (CSRR) design. The sensor is specifically engineered to distinguish carotid artery atherosclerotic plaques.

Research has revealed a direct relationship between sensitivity and both the fill factor and the Q (where Q is loading quality factor). In broad terms, a higher Q value tends to boost sensor sensitivity, thanks to its capacity to amplify the neighbouring electric field intensity [112,113]. This study presents a new microwave sensor design for continuous blood glucose monitoring. It consists of two split-ring resonators, one for glucose interaction and the other as a reference. The sensor showed promising performance in comparison with commercial sensors during an oral glucose tolerance test. Interference tests revealed negligible effects from common interferents, indicating the sensor's effectiveness in glucose measurement [112]. They develop an analytical method to link the response of a spiral microstrip resonator to the relative dielectric constant of a lossy superstrate, like biological tissue. By modifying an analytical equation and simulating with digital phantoms, we find the resonator's parameters using particle swarm optimization. These parameters are then used to derive a new analytical equation, which is validated against physical phantom measurements with less than 3.67 % error [113].

Researchers continue to explore innovative antenna designs and signal processing algorithms to optimize the efficiency of these sensors. Examining the Influence of Concurrent Changes in Glucose and Albumin Concentrations on Sensor Readings and Evaluating Sensor Selectivity [114]. This study examines the specificity of microwave planar resonant sensors in gaging glucose concentrations in multiconstituent solutions. Three sensors are evaluated, showing a lack of selectivity against variations in albumin concentration. Strategies to address this challenge are proposed based on the findings.

Ongoing research focuses on developing robust sensor technologies that can overcome these challenges and provide users with a convenient and reliable method for continuous glucose monitoring.

In conclusion, the electromagnetic interaction between microwaves and biological tissues is at the core of microwave glucose sensors. These sensors leverage the sensitivity of dielectric properties to glucose conc., offering a non-invasive and promising method to glucose monitoring for individuals with diabetes. While advancements continue to be made in sensor design and technology, the potential for widespread adoption of microwave glucose sensors as a valuable tool in diabetes management is evident, paving the way for Enhanced patient results and quality of life.

c. Designs of microwave glucose sensors

In the recent years, there has been lot of work going on for designing new microwave sensors.

The design of microwave glucose sensors involves careful consideration of the frequency range, antenna configuration, and signal processing techniques to achieve accurate and reliable measurements. Despite the non-invasive nature of microwave glucose sensors, challenges remain, particularly in addressing potential interference from surrounding tissues and compensating for variables that could influence the dielectric characteristics of tissues unrelated to glucose concentration. Additionally, factors such as body movement and environmental conditions can influence sensor performance. The challenge lies in optimizing these parameters to balance depth of penetration with signal sensitivity, ensuring effective monitoring without compromising accuracy. Another main challenge lies on the fact that the design should be compact and should also provide space to hold samples. For this, the main precaution one should take is to design such tracks that doesn't allow changes in the scattering parameters even on bending and tilting. Also, during

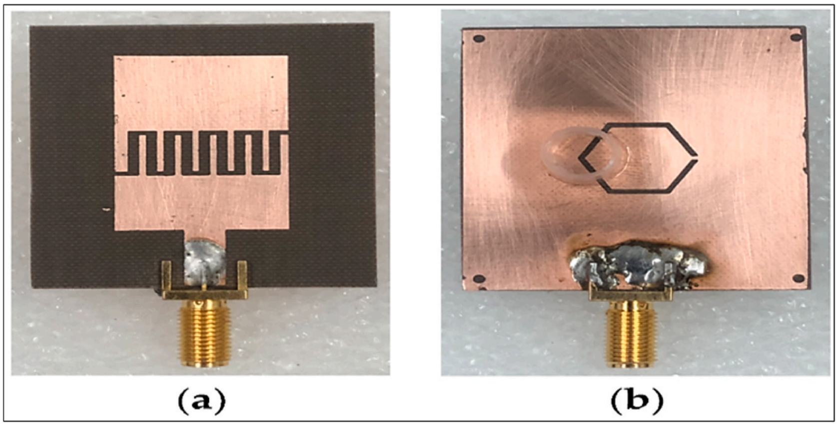

Fig. 1. The microwave sensor with a hexagonal configuration of split-ring resonators (CSRR) is depicted (a) the top view and (b) the bottom view [115].

tests, the movement should be as small as possible for lab prototypes. This can provide accuracy and reproducibility. One research [115] introduced a microwave-based sensor (in Fig. 1) for non-invasive glucose level calculated in liquid solutions. A planar interdigital capacitor is integrated with a hexagonal complementary split-ring resonator (CSRR) known for its intense electric field. Glucose solutions were tested, and changes in resonance frequency (Fr) and reflection coefficient (S11) were observed. The sensor precisely measured glucose levels in 0–149.9 mg/dL, with a peak sensitivity at 37.49 mg/dL: 10.0229 dB per mg/dL (S11) and 1.729 MHz per mg/dL (Fr). These findings suggest potential medical applications for glucose level monitoring.

In [116] Fig. 2, two rings consist of silver-layered copper wire with a diameter of 1.5 mm, exhibiting resonant frequencies that differ by around 250 MHz. In this configuration, the resonant frequency of the sensing ring is lesser than that of the reference ring, primarily attributed to dielectric loading caused by the presence of the body. The recorded change in frequency is 600 kHz, representing a partial shift in frequency is of 0.034 % at 1.74 GHz. The quality factor (Q) of the sensing peak was determined to be approximately 800 when measured in the air and drops to around 80 when on the body.

In [117], the ceramic substrate, overlaid with a 50 μm-thick layer of silver paste, underwent laser patterning and a two-step annealing process at 600 °C and 880 °C. Soldered to conductors, the sensor's unique pattern, a modified Hilbert-defined closed curve, aligns with recent microwave studies. Utilizing a ceramic substrate with a relative permittivity is roughly 9.199 and size is 20.4 mm × 40.4 mm × 1 mm, the sensor's design parameters ($h = 1$ mm, $w = 0.1$ mm, $s = 2.6$ mm) ensure optimal performance. The configurations are shown in Fig. 3.

The development of a microwave sensor, utilizing a modified Hilbert-defined closed curve, offerings a non-invasive glucometer designed to monitor glucose levels in aqueous solutions. This sensor offers a non-damaging method, establishing a linear relationship (0.0156 dB/(mg/dL)) between S21 and D-glucose conc. at approximately 5.99 GHz. With a minimum detectable resolution of 1.92 mg/ml for a 500 μL MUT volume, the sensor addresses temp. Fluctuation through a corrective mechanism (0.05 dB/°C and 0.15 dB/°C) in the temperature ranges of 26–34 °C and 36–40 °C. The results highlight the sensor's potential for real-time glucose measurement, positioning it as a platform for future bloodless glucometer development.

A study in Ref. [118] presents a novel liquid glucose sensor utilizing a complementary split-ring resonator operating within the microwave frequency range. The sensor as shown in Fig. 4 enables non-invasive detection of glucose across a range of concentrations from 0 mg/dL to 400 mg/dL by integrating a liquid system. Continuous monitoring of glucose concentration is achieved by analysing the transmission coefficient $S21$ as the primary detecting parameter. The relation between $S21$ and glucose concentration is investigated using an equivalent circuit model. Furthermore, to mitigate systematic errors arising from temperature fluctuations, the sensor undergoes assessment in two temperature settings: consistent temperature and temperature that varies with time. In the latter scenario, a function for temperature correction is developed based on the correlation between temperature and $S21$ variations observed in deionized (DI) water. By applying this correction function to glucose solutions, temperature-induced artifacts are effectively mitigated. Consequently, the $S21$ exhibits a negligible variation of 0.03 dB across the entire glucose level of 0 mg/dL to 400 mg/dL.

A novel technique introduced to enhance the reaction resolution of microwave biomedical resonant sensors, tackling challenges like broad resonance peaks and frequency discretization issues. The proposed algorithm sharpens the sensor's response and improves the accuracy of resonance frequency estimation. Validation is conducted using synthetic data and real-world measurements from a microwave resonant sensor developed (as shown in Fig. 5) for monitoring blood glucose level, demonstrating its effectiveness. This approach offers a practical solution to advance the execution of microwave resonant sensors in biomedical applications, especially for blood glucose monitoring [119].

In [120], authors introduced an RF sensor (as shown in Fig. 6) according to a stepped impedance resonator for this purpose. Placed on the hand, it detects blood sugar variations by monitoring dielectric constant changes. The sensor runs at 3.5279 GHz with a Quality factor of 1455. We validated it with a microfluidic device simulating human blood veins. Glucose solutions from 0 to 240 mg/dL were tested, revealing a sensitivity of 264.2 kHz/mg·dL−1 and a limit of detection (LOD) of 29.89 mg/dL. This sensor offers promise for continuous monitoring of blood glucose levels non-invasively.

In [121], the paper introduces an oval-designed sensor for measuring glucose level in water as depicted in Fig. 7. It is influenced by metamaterial characteristics and consists of a sensing layer between two nozzle-shaped microstrip lines. The sensor operates optimally at 3.914 GHz with dual negative metamaterial characteristics. Its responsiveness is approximated at 0.0369 GHz/(30 mg/dL) for glucose solutions. The sensor parametric structure and examination were done using CST microwave studio simulation software.

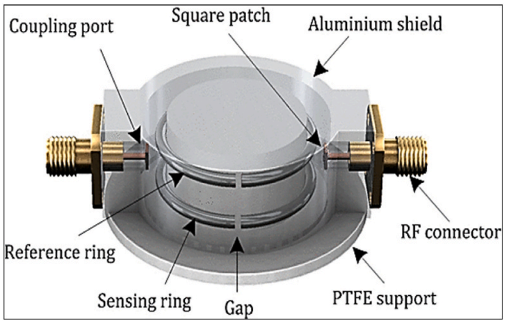

Fig. 2. The proposed sensor features a three-dimensional architecture utilizing discrete double split-ring resonators [116].

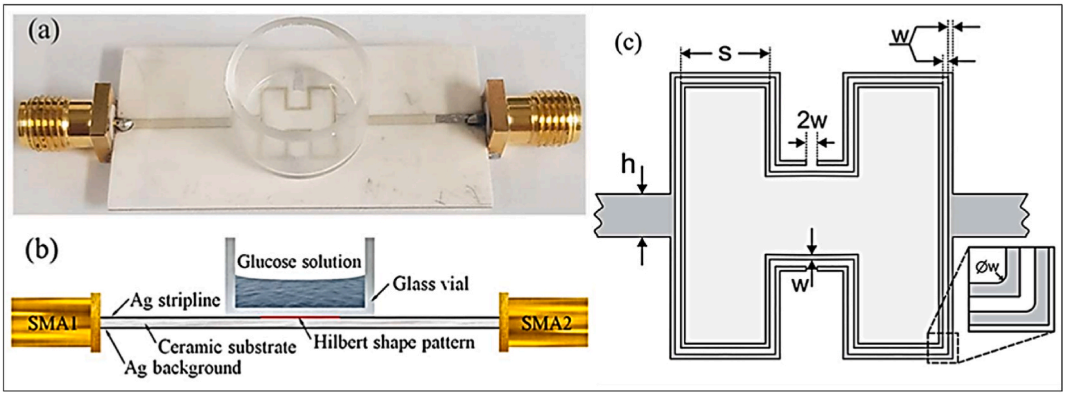

Fig. 3. A sensor designed based on Hilbert principles, enclosed within a quartz vial: (a) Visual representation; (b) diagram depicting a cross-sectional view of the structure; (c) configuration of the sensor's components [117].

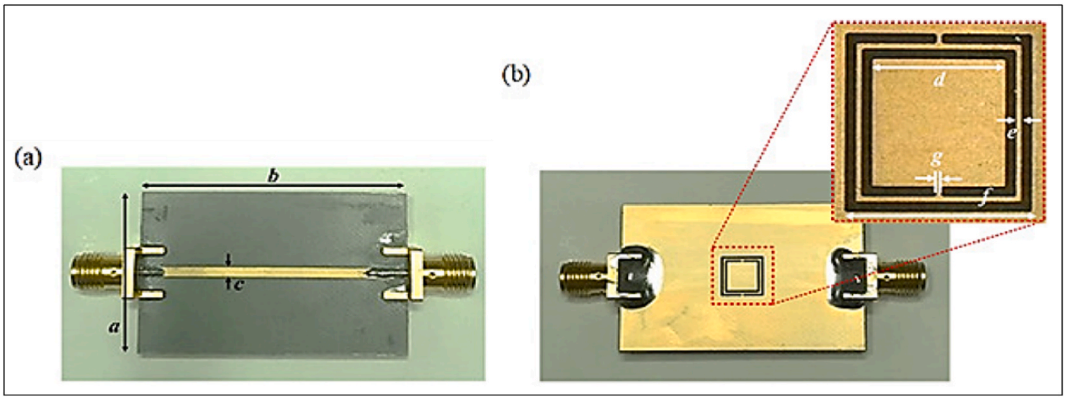

Fig. 4. The fabricated sensor. (a) Signal line patch of the sensor; (b) ground plane of the sensor and resonating part of sensor [118].

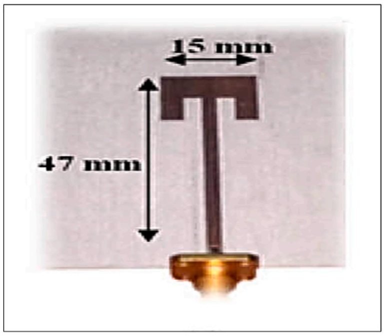

Fig. 5. Microwave glucose sensor deign [119].

Experimental verification supports the findings. The sensor shows potential for qualitative analysis of glucose levels in water solutions.

In [122], researchers are grappling with sensor selectivity issues, particularly in measuring glucose levels amidst interference from other components. This research investigates the selectivity of microwave planar resonant sensors in detecting multicomponent solutions. Three sensors are used, two simplified for size reduction, while the third enhances sensitivity. The findings reveal a significant influence of albumin concentration on glucose measurements, highlighting a lack of selectivity across all sensors.

In [123], the paper introduces that the non-invasive monitoring of blood glucose levels using microwave frequencies is typically considered unreliable in terms of the consistency of measurements, largely due to interference from leaky waves between the device and its surroundings. This study tackles this issue by addressing these leaky modes using surface electromagnetic waves from a bent G-line. The procedure involves creating a controlled volume of blood-filled skin tissue via vacuum suction, partially wrapping it with a

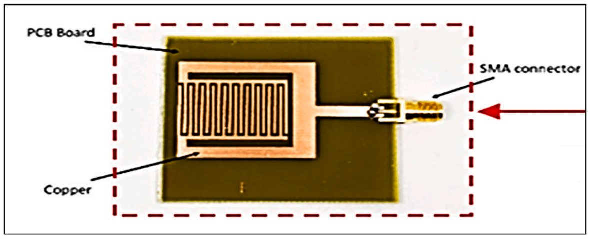

Fig. 6. An RF sensor incorporates interdigital and Stepped Impedance Resonator structures, with design parameters defining its functionality and performance [120].

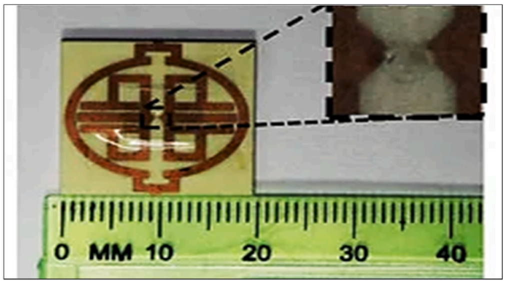

Fig. 7. Sensor leveraging metamaterial properties [121].

bent G line covered in a 3 mm wide gelatin/glycerin composite, and then non-invasively measuring blood glucose levels using a network analyzer. A strong linear correlation was observed at 4.5 GHz between the measured S12 parameters, and the blood glucose levels, showing high reproducibility and agreement with results from traditional invasive methods. These findings suggest promising potential for detecting bodily imbalances non-invasively.

In [124], author presents that in the last ten years, deep learning (DL) has increased interest for its role in analysing biomedical and healthcare issues, surpassing traditional methods and human expertise in identifying key characteristics and completing complex tasks. With the proliferation of data in various formats such as images, sounds, text, and signals from medical tools and programs, the concept of big data has emerged. DL, as a type of machine learning algorithm with multiple hidden layers arranged in a network structure, is adept at analyzing large medical datasets. This trend aligns with the growing shift towards personalized healthcare, facilitated by mobile health (mHealth) applications. DL can effectively analyze the vast amount of data generated by these applications. This study offers a overview of DL principles and trends in healthcare, focusing on its applications in biological systems, electronic health records, medical imaging, and physiological signals. It also addresses challenges in DL and suggests future research directions to improve health management using physiological signals and internet technology.

In [125], the paper presents that Continuous tracking of blood glucose levels is crucial for effectively managing diabetes often involving painful finger pricking. Current research explores using electrocardiograms (ECG) for non-invasive monitoring. The study where an oral glucose tolerance test conducted on thirteen adults, analyzing 9 ECG segments. Findings reveal consistent patterns in certain segments like QT, ST, and QTC, with strong correlations to glucose levels. Other segments, like R-H and P-H, show weaker correlations.

In [126], paper introduce that diabetes cases have surged globally, becoming a leading cause of death. This metabolic disorder disrupts blood glucose regulation, leading to high sugar levels. Genetics, sedentary lifestyles, and poor diets contribute. Monitoring involves painful finger pricking, prompting the search for non-invasive methods to alleviate inconvenience and infection risks.

In [127], Measuring glucose concentrations at microwave and millimeter-wave frequencies faces challenges due to weak dependence on permittivity and interference from ambient waves. Nevertheless, this research highlights the existence of a strong correlation between the concentration of glucose in a solution and the permittivity of blood during resonance of whispering gallery mode. This was achieved by employing a sensor that consists of a vacuum suction aspirator wrapped with a G-line. Fixed volumes of tissue or glucose/H_2O solution were created for in-vivo and ex-vivo measurements. Results show strong correlations between glucose levels and S21 parameters at 2.18 GHz in the in-vivo study and at 56.6 GHz in the ex-vivo study. These findings suggest potential for non-invasive glucose monitoring at millimeter-wave frequencies, consistent with previous research.

In [128], paper introduces the importance of highly confined fields for biosensors aimed at glucose measurements. Creating concentrated energies at specific points enhances sensitivity in the sensing region. By minimizing losses from radiation through air, this principle facilitates the design of highly sensitive glucose monitoring sensors. The concept is exemplified through a biosensor design presented in the paper.

In [129], the paper introduces a novel CGM metric, gradient, for predicting nocturnal hypoglycemia in insulin-treated diabetes. By combining mean sensor glucose (MSG) with gradient, a new metric (MSG + gradient) was formed and tested using data from 1921 diabetes patients. The MSG + gradient method showed superior specificity and sensitivity compared to conventional metrics like LBGI and CV, across four predictive algorithms. This combined method holds promise for improved prediction of nocturnal hypoglycemia, with further validation needed in future studies.

In [130], the paper proposes an ECG-based technique for non-invasive sensing of blood glucose (BG) levels across three ranges: low, moderate, and high. Through fasting and oral glucose tolerance tests on 21 adults, continuous ECG signals were recorded. An approach combining DBSCAN-CNN was used for ECG preprocessing and BG range classification. Results showed high accuracy in classification: 87.94 % for low, 69.36 % for moderate, and 86.39 % for high glucose levels. Visualization of ECG highlights for different BG ranges revealed distinct patterns. Prediabetes/diabetes screening sensitivity reached 98.48 %, with 76.75 % specificity. This approach holds promise for practical BG monitoring and screening applications.

In [131], the paper proposed a study that presented a compact contact-based sensor on a flexible substrate for glucose sensing. Utilizing a bifilar spiral resonator (BSR), it detects resonance frequency shifts at ultrahigh frequencies (UHFs) due to glucose concentration changes. Experimental validation with aqueous and serum blood solutions demonstrated a positive and a direct relationship exists between glucose conc. and the shift in resonant frequency. The sensor exhibited high sensitivity (250 MHz/(mg/mL) for glucose.

In [132], the paper introduced a new non-invasive method for quickly assessing HbA1c levels in diabetes patients using 60-s single-lead ECG data was developed. It achieved high accuracy and outperformed traditional methods, suggesting practical implementation for efficient HbA1c detection without discomfort.

In the work [133] recognizing the clinical significance of glycaemic variability and hypoglycemia, there remains a lack of consensus on a unified assessment method. This study introduced the gradient variability coefficient (GVC) as a novel metric to address this issue. Data from continuous glucose monitoring were analyzed, including records from 104 individuals with type 1 diabetes mellitus (T1DM) and 1190 individuals with type 2 diabetes mellitus (T2DM). Simulated CGM waveforms were used to compare GVC with other metrics in capturing glucose fluctuations, and the relationship between GVC and hypoglycemia risk was assessed using receiver operating characteristic (ROC) curves.

In [134], the paper proposed a new model based on Lorentz's theory replaces the conventional Cole-Cole model to predict changes in resonant frequency induced by glucose concentration alterations. This model informs the development of a contact-based meander-line antenna sensor (CMS) with high sensitivity. Experimental validation confirms the model's accuracy, showing a direct relationship between resonant frequency shifts, S-parameter magnitude, and glucose concentration.

In [135], the paper proposed the early detection of prediabetes is crucial for preventing complications and mortality. However, current methods involve invasive finger pricking, causing discomfort. This study explores non-invasive methods using EEG frequency parameters to estimate blood glucose levels. By analyzing EEG signals from different positions during an oral glucose tolerance test on 25 individuals, specific patterns were identified. Results show high sensitivity in certain positions, indicating the potential integration of EEG parameters into wearable devices for non-invasive prediabetes diagnosis and continuous blood glucose monitoring.

In [136], authors provide a practical implementation of a differential microstrip microwave sensor designed for real-time monitoring of *Escherichia coli* (*E. coli*) proliferation on solid agar substrates. The sensor comprises two flat microstrip ring resonators connected with a one-port power divider. The sensing resonator operates at a frequency of 1.5 GHz with an amplitude of −10.21 dB, whereas the reference resonator works at 1.798 GHz with an amplitude of −11.75 dB. The analysis involves measuring fluctuations in resonant amplitude., we tracked *E. coli* growth patterns at various glucose concentrations in Luria-Bertani (LB) agar. Complete suppression of proliferation was observed at a 10 % glucose conc. This study demonstrates the potential of microwave sensors in assessing the impact of nutritious factors on bacteriological proliferation.

In [137], the authors introduce a new adaptable multimode microwave sensor designed for the real-time, non-invasive monitoring of glucose. This sensor integrates resonance and transmission sensing functions by employing dynamic controllable spoof surface plasmon polariton transmission lines and a multimode array resonator that relies on spoof localized surface plasmon. Bias voltage adjustment controls the sensor's behaviour, enabling glucose monitoring through changes in resonance frequencies and transmission coefficient amplitudes. Experimental results in the glucose range of 0–800 mg/dL show high sensitivity: 9.86 × 10−2 MHz/(mg/dL) for resonance sensing and 2.00 × 10−2 dB/(mg/dL) for transmission sensing, with strong linear correlation and robust error correction capabilities.

In [138], the study introduces a non-invasive and painless method for continuous monitoring of blood glucose levels using two finger-sized ultrawideband antennas. To address challenges with antenna miniaturization, a dual-band fusion strategy and an improved long short-term memory (LSTM-R) model based on ultrawideband microwave technology are proposed. The framework shows high accuracy and robustness in predicting blood glucose levels, confirmed through simulation and experimentation. Testing on glucose solutions results in a root-mean-squared error of 4.2367 mg/dL and a mean absolute relative difference of 2.79 %. Human trials demonstrate a low MARD of 5.9 % for non-invasive estimation, with results within clinically acceptable ranges according to Clark error grid analysis.

In [139], the research introduces a microwave sensor for tracking blood sugar concentration in diabetes. The sensor, composed of eight hexagonally shaped complementary split-ring resonator cells on a Rogers RO3210 substrate, exhibits strong sensitivity to minute changes in glucose dielectric properties. Simulations in a 3D full-wave EM simulator show superior sensitivity compared to individual resonators. Experimental validation via a vector network analyzer confirms the sensor's effectiveness, demonstrating a resonance frequency shift of approximately 3 MHz/(mg/dL) in response to blood glucose concentration. This design shows promise for non-invasive wearable glucose monitoring.

In [140], authors investigated resonant sensors working in the microwave frequencies and proposed them for finding variations in blood glucose concentrations using non-invasive methodology. A filter design based SIW cavity sensor has been designed along with metamaterial split ring structure. The sensor has directly been tested over the volunteers both invasively and non-invasively for comparisons.

In [141], the article introduces a microwave-based sensor for non-invasive glucose detection., utilizing sodium chloride alongside glucose. Dielectric properties of glucose and NaCl solutions are analyzed, and a switching circuit is used to remove temperature-induced effects. Dual sensing is achieved with a resonator employing an interdigital capacitor (IDC). Real-time storage of reflection coefficient discrepancies enables continuous detection. Reflection coefficient alterations for glucose (0–400 mg/dL) and NaCl (500–900 mg/dL) are 0.41 dB and 1.43 dB, respectively. Results show the sensor's ability to identify minor glucose concentration changes amidst diverse substances in blood.

In [142], the paper presents a CMOS transmitter and PCB probes for glucose sensors operating in microwave or millimeter-wave frequencies. The transmitter fabricated using TSMC 90-nm CMOS technology, outputs power from 13.85 to 16.95 dBm over frequencies of 32–36 GHz, consuming 254.6 mW. PCB probes, made with Rogers RO4003C material, are utilized for experimental tests on glucose phantoms. Discrepancies in transmission losses for phantoms with glucose concentrations of 100 and 200 mg/dL reach up to 3.63 dB at frequencies of 29.5–33 GHz. Using the CMOS transmitter, experiments show a difference in received power levels of up to 8.9 dB at 33.22 GHz for phantoms with glucose concentrations of 100 and 200 mg/dL across the range of frequencies 32–36 GHz.

In [143], authors proposed a Band-stop filter design sensor that is further developed on the platform of substrate integrated waveguide cavity to perform blood glucose measurements non-invasively. Working on the principle of localised field enhancement, the calculations shows that the proposed SIW sensor provides good results by considering fingertip positioning and by considering the effected due to fingerprints.

In [144], a microwave sensor resonating at two different frequencies has been proposed operating at around 5 GHz and 7 GHz. The sensor is designed on the aspects of split ring resonator and has been designed to find/extract the real part of the effective permittivity of the proposed sample. With several advantages such as sensing at different bands, high quality value, highly sensitive, and miniaturized dimensions, this sensor has achieved multiple results with high accuracy.

In [145], the article presents a highly sensitive microwave sensor for dielectric sensing, addressing cross sensitivity caused by environmental factors like temperature. It utilizes a differential measurement technique to compare two transmission resonance frequencies, ensuring accuracy over time. The sensor features a spiral resonator with an extended horizontal microstrip line (EH-ML) coupled to a microstrip transmission line (MTL), enhancing sensitivity and resolution. Achieving a frequency detection resolution (FDR) of 44 MHz and a sensitivity of 0.85 % at a maximum permittivity of 78.3, the sensor's results from theoretical analysis, simulation, and measurement are in good agreement, demonstrating its effectiveness. With low complexity, high resolution, and precision, the sensor holds promise for health, chemical, and agriculture applications.

2.1. Advancement in microwave glucose sensors to make these portable and compact in size

The future of microwave glucose sensors holds great promise, with ongoing efforts focused on improving their performance and user-friendliness. These sensors have the potential to transform glucose monitoring by providing continuous and non-invasive measurements, thus enhancing diabetes management. Continued research and development are expected to enhance sensor accuracy, sensitivity, and selectivity, ensuring more precise and reliable glucose readings. Moreover, merging these sensors into wearable devices such as smartwatches will make glucose monitoring more convenient and accessible for users. Advancements in wireless communication technologies will further enable seamless data transmission and real-time monitoring, empowering individuals to actively manage their health. In summary, microwave glucose sensors have a bright future, offering significant improvements in the lives of those living with diabetes.

To improve the portability and compactness of microwave glucose sensors, it is worth exploring strategies to eliminate the cumbersome Vector Network Analyzers (VNAs) that are traditionally used in conjunction with these sensors. One possible avenue is

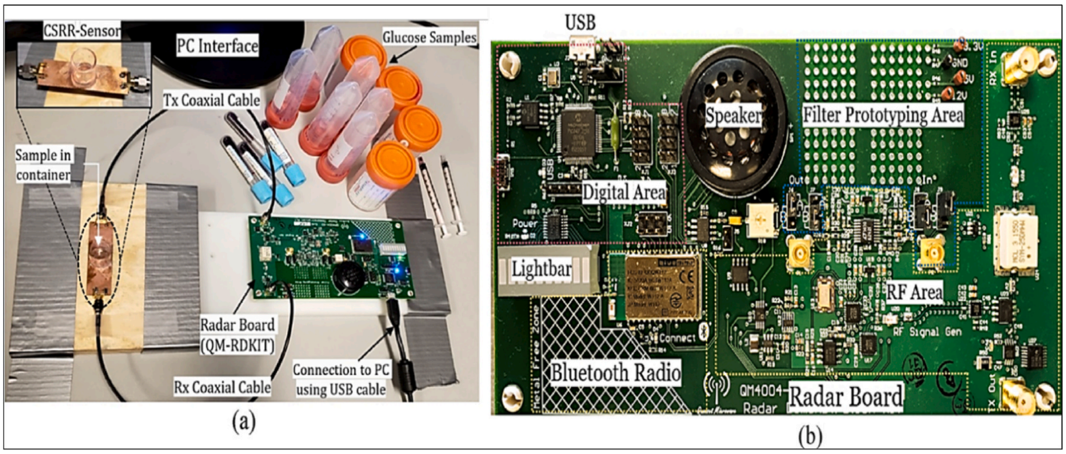

Fig. 8. (a) A compact arrangement integrating the sensor with a low-frequency radar board for versatile usage, (b) The primary components within the radar board: digital, Bluetooth radio, RF, filter prototyping, and lightbar for audiovisual feedback [146].

the development of smaller and more integrated electronic components that can carry out similar functions as VNAs, but in a significantly reduced form factor. These components can be purposefully designed to fit within the confines of portable devices, such as smartwatches or smartphone accessories. Another approach involves the incorporation of VNA functionality directly into the sensor itself. This can be accomplished through advancements in microelectronics and sensor technology, which would enable the inclusion of on-chip circuitry or signal processing algorithms capable of facilitating impedance measurements by the sensor without the requirement of external equipment. Moreover, researchers are actively investigating novel sensing techniques and materials that have the potential to fully eliminate the necessity of VNAs. One such promising technique is impedance spectroscopy, which allows for the immediate measurement of the electrical characteristics of materials, including glucose levels, without the need for complex external instrumentation. By embracing these aforementioned approaches, it becomes feasible to render microwave glucose sensors more compact and portable, thereby opening up new avenues for non-invasive glucose level measuring in everyday life.

A portable model of a small-scale detector was created utilizing an economical, energy-efficient radar module to operate the system, substituting the conventional Vector Network Analyzer (VNA) as shown in Fig. 8. The usage of the QM-RDKIT with frequency modulated continuous wave functionality made possible the connection of the complementary split ring resonator sensor within the ISM frequency range (2.4–2.5 GHz). The radar board consolidated an RF section for producing and converting signals, with a Phase Lock Loop and Voltage Controlled Oscillator ensuring signal stability. The output of the sensor underwent mixing, filtering, and digitization before being processed by the microcontroller integrated onboard. Glucose samples were precisely assessed and transferred onto the sensor using a micropipette, with radar signals triggered for data collection. Verification of consistency included three attempts per sample, resulting in minimal error. Acquired raw data were transmitted to a mainframe computer through USB or Bluetooth. Processing involved examining average voltage signals to establish energy density, capturing distinctive variations in dielectric properties among glucose samples. Further analysis employing the PCA classification algorithm facilitated arranging glucose samples into clusters using principal components [146].

2.2. Parameters for improvement in microwave glucose sensors

Sensitivity: Microwave glucose sensors may struggle to detect low concentrations of glucose level. This limitation is particularly important in diabetes management, where precise monitoring of blood glucose levels, even small amounts of high glucose level are crucial for keeping our bodies healthy and avoiding problems. A lack of sensitivity could result in inaccurate readings, leading to incorrect treatment decisions and serious health risks for individuals with diabetes. Due to this these sensors are not available in market for medical purpose because this leading to incorrect diagnosis. In order to enhance the overall sensitivity, the researchers need to focus on developing such advanced sensors that can result in high sensitivity. Sensors designs should have high confined fields and highly concentrated energies with pin-pointed beams so that they can very efficiently measure the glucose on-body. This will further help in pointing the targeted location with minimum geometrical changes of the body.

Specificity: Specificity refers to the sensor's ability to accurately sense and calculate glucose without interference from other substances present in the sample. Microwave glucose sensors may face challenges in achieving high specificity, as they may inadvertently detect other molecules or compounds present in biological fluids alongside glucose. This lack of specificity can lead to false readings or inaccuracies, undermining the reliability of glucose measurements obtained with these sensors. The critical challenge lies in the selectivity of glucose concentration in response to fluctuations in concentrations of other components or parameters. For example, immediate variations in the concentrations of glucose level can have an effect on the final measurements. For improving this parameter, the sensors developed should be highly frequency specific. Means, the frequency at which the sensor is operating is highly important. Not all frequencies respond to all analytes. There is a need to identify such frequencies, that detect glucose or analytes very specifically.

Complexity of Calibration: Calibration is the process of adjusting and fine-tuning a sensor to ensure accurate and reliable measurements. Microwave glucose sensors often require complex calibration procedures, which can involve precise adjustments to account for factors such as temperature variations, signal drift, and sample composition. These calibration processes may be time-consuming and require specialized expertise and equipment, posing challenges for routine use in clinical or home settings. For lab experiments, the tests should be performed in a clean room facility with constant temperature and atmospheric levels. Further for real time measurements, the robustness of the sensor is very important.

Interference: Microwave signals used in glucose sensors may be susceptible to interference from external sources, such as electromagnetic fields, ambient noise, or variations in environmental conditions. Interference can distort or disrupt the signals received by the sensor, leading to errors in glucose measurements. Shielding the sensor from external interference and implementing signal processing techniques to filter out unwanted noise are imperative to reduce the impact of interference on the accuracy of glucose readings. This parameter has same conditions to follow as mentioned above in the complexity of calibration paragraph.

Limited Penetration Depth: Microwave signals may have limited penetration depth into biological tissues, restricting their ability to accurately measure glucose concentrations in deeper layers of skin or tissue. This limitation can affect the reliability of glucose measurements obtained with microwave sensors, particularly in applications where non-invasive or minimally invasive monitoring is desired. Improving the penetration depth of microwave signals or developing alternative sensing techniques that can penetrate deeper into tissues may help overcome this limitation. For this, one needs to follow the principle of frequencies which gives an inversely proportional relationship between depth and frequency. Lower the frequency, higher the depth. Also, the narrow beam sensor designs may prove more useful in such case.

Cost and Accessibility: Microwave glucose sensors can be costly to produce and maintain, making them less affordable to people or healthcare services with limited economic resources. The steep expense of equipment, materials, and specialized expertise required for sensor development and calibration can hinder widespread adoption of microwave glucose sensors, particularly in resource-constrained settings. Addressing cost-related barriers and increasing affordability and accessibility are crucial for expanding the reach of glucose monitoring technologies. Choosing low-cost material and fabrication techniques with simple designs can support cost factor. Further the measurement instruments such as vector network analysers can be replaced with small instruments or some wireless measurements set ups.

Size and Portability: Some microwave glucose sensors may be bulky and impractical for continuous monitoring in everyday settings or wearable devices. The size and portability of glucose sensors are important considerations for user comfort, convenience, and adherence to monitoring regimens. Bulky sensors may restrict mobility and limit the usability of monitoring devices, particularly for individuals who prefer discreet or lightweight solutions. Developing miniaturized and portable microwave glucose sensors that can be integrated into wearable devices or smartphone applications may enhance user experience and improve usability. For this, one can work on metamaterial-based surfaces that can give excellent properties over a very compact platform and can be flexible and easily integrable for solving portability issues.

Table-1 shows the comparative assessment of the selected glucose sensors as cited in this work based on the frequency shift approach or magnitude variation approach of blood glucose measurement. Most of the compared works in the table followed the method of finding sensitivity in terms of scattering parameters i.e. either reflection coefficient (S11) or transmission coefficient (S21). Few researchers have followed the approach to find voltage for testing the sensitivity. For invitro measurements, solution-based tests have been performed primarily and invivo (on-body or blood serum) measurements have been performed by some researchers who have achieved good sensitivities. While most sensors have been focused by finding parameters for testing sensitivity, detection limits; only a few have achieved good selectivity.

2.3. Future improvement in microwave glucose sensors to overcome its limitation

a. **Enhanced Sensitivity:**
  - Explore novel sensor designs: Research can focus on developing innovative sensor designs that optimize the interaction between microwave signals and glucose molecules, thereby increasing sensitivity.
  - Signal amplification techniques: Investigate methods to amplify the weak signals generated by low concentrations of glucose, such as incorporating amplifiers or signal enhancement technologies into sensor platforms.
  - Advanced signal processing algorithms: Develop sophisticated algorithms to analyze and extract subtle changes in microwave signals corresponding to glucose concentrations, improving sensor sensitivity and accuracy.

Table 1
Comparative assessment of the cited glucose sensor based on the frequency shift approach of blood glucose measurement.

Ref.	Sensor	Frequency	Measured parameter	Sensitivity	Detection limit	Selectivity	On-body tests done
77	Electromagnetic Sensor	Optimal frequency for the inductors	Output voltage	~0.22 mV/(mg/dL)	Not specified	Not specified	No
85	CSRR Microwave Sensor	2.4–2.5 GHz	S21	0.94 MHz/(mg/dL)	1 mg/dL	Not specified	Yes
86	EM Sensor	0.5 and 4 GHz	S11	Picomolar	Not specified	High	Yes
106	Planar sensor	357.8 MHz	S11	0.795 %	Not specified	Not specified	No
108	Microstrip antenna resonator	1.96–2.18 GHz	Resonant frequency shift of S11	0.0003 GHz per mg/dL	Not specified	Not specified	No (Based on Phantoms)
112	Resonant sensor	9 GHz	S21	7.67 MHz (mg $dL^{-1})^{-1}$.	Not specified	Not specified	Yes
115	Interdigital Capacitor coupled with split-ring resonator	1–5 GHz	S11	1.73 MHz per mg/dL and 10.023 dB per mg/dL	Not specified	Not specified	No
116	Double Split-ring resonators	1.4GHz–1.8 GHz	Resonant frequency shift of S21; Bandwidth change of S21	328.7 kHz per mM for resonant frequency shift method; 437.5 kHz per mM for the bandwidth change method	.75 mM for the bandwidth change method	High	Yes
117	Hilbert Shaped microwave sensor	6 GHz	S21	~0.0037 dB/(mg/dL)	1.92 mg/dL	Not specified	No
121	Oval-shaped sensor	3.914 GHz	S21	0.037 GHz/(30 mg/dL)	Not specified	Not specified	No
122	Planar microwave sensor	~4 GHz	S21	High	0.058–0.098 g/dL	High	No
131	Bifilar Spiral Resonator	~650 MHz	S11	130 MHz/mg/ml & 4 dB/mg/ml	<0.5 mg/ml	Good	No (Blood serum)
148	Microwave resonator	5.5 GHz & 8.5 GHz	S21	3.53 and 3.58 MHz/(mg/dL)	Not specified	Not specified	Yes

b. **Improved Specificity:**
    - Selective receptor integration: Incorporate selective receptors or biomolecules onto sensor surfaces that specifically bind to glucose molecules, enhancing the sensor's ability to discriminate glucose from other interfering substances.
    - Surface modifications: Implement surface modifications or coatings that minimize non-specific binding and enhance the selectivity of the sensor for glucose detection.
    - Multivariate analysis techniques: Employ advanced data analysis techniques, such as multivariate analysis or machine learning algorithms, to differentiate glucose signals from background noise and interference, improving specificity.

c. Simplified Calibration:
    - Automation of calibration procedures: Develop automated calibration methods or calibration routines embedded within sensor systems to streamline the calibration process and reduce the need for manual intervention.
    - Self-calibrating sensors: Explore the feasibility of designing self-calibrating sensor systems capable of continuously monitoring and adjusting sensor performance based on internal reference standards or built-in calibration algorithms.

d. Noise Reduction and Interference Mitigation:
    - Improved shielding techniques: Enhance sensor design with improved shielding materials or configurations to minimize external electromagnetic interference.
    - Advanced signal processing: Develop sophisticated signal processing algorithms capable of filtering out noise and interference while preserving the integrity of glucose signals, improving the reliability and accuracy of glucose measurements.

e. Increased Penetration Depth:
    - Novel sensor geometries: Investigate novel sensor geometries or configurations that optimize the penetration depth of microwave signals into biological tissues, enabling more accurate measurements of glucose concentrations in deeper tissue layers.
    - Multi-frequency sensing: Explore multi-frequency sensing approaches [147] that leverage different microwave frequencies or wavelengths to penetrate varying tissue depths and improve measurement accuracy.

f. Cost Reduction and Miniaturization:
    - Affordable materials and fabrication techniques: Utilize cost-effective materials and manufacturing processes or even integrating material-based Bio-Nanocomposites, such as additive manufacturing or printed electronics, to reduce sensor production costs.
    - Miniaturized sensor platforms: Develop miniaturized sensor platforms [148] that are portable, lightweight, and suitable for integration into wearable devices or point-of-care diagnostic systems, enhancing accessibility and usability.

g. Integration with Smart Technology:
    - Smartphone connectivity: Integrate microwave glucose sensors with smartphone apps or wireless communication protocols to enable real-time data transmission, remote monitoring, and data analysis.
    - Cloud-based analytics: Leverage cloud-based data analytics platforms to aggregate and analyze glucose data from multiple sensor users, providing personalized insights and support for healthcare professionals and individuals managing diabetes.

By addressing these areas of improvement, future advancements in microwave glucose sensor technology hold the potential to overcome existing limitations and usher in a new era of precise, reliable, and accessible glucose monitoring for individuals with diabetes and other metabolic disorders.

3. Conclusions

This paper in conclusion highlights the main discoveries and underscores the increasing significance of microwave glucose sensors for overseeing blood glucose concentration non-invasively. It highlights the capability of these sensors to revolutionize diabetes supervision, enhance patient experience, and pave the way for continuous, real-time monitoring in the future. This review underscores the notable strides made in the realm of microwave glucose sensors. These sensors, boasting a non-intrusive approach and the prospect of continuous monitoring, hold immense potential in transforming the landscape of diabetes management. Nevertheless, certain challenges, including refining sensor accuracy, minimizing power consumption, and enhancing user comfort, remain pertinent and warrant attention. Future research endeavours should be directed towards surmounting these obstacles, paving the way for microwave glucose sensors to emerge as a compelling alternative to conventional glucose monitoring methodologies. Moreover, collaborative efforts involving engineers, medical practitioners, and patients are imperative, ensuring not only the technical robustness but also the user-friendly and clinical relevance of the technology. Through sustained research and development, microwave glucose sensors stand poised to make substantial contributions, significantly elevating the standard of living for individuals grappling with diabetes. The review has illuminated the remarkable progress within the realm of microwave glucose sensors, showcasing their potential as game-changers in diabetes management. The non-invasive nature and the promise of continuous monitoring make them particularly noteworthy in advancing patient care. However, challenges persist, emphasizing the need for ongoing efforts to enhance sensor accuracy, reduce power consumption, and optimize user comfort. In comparison to other non-invasive techniques, microwave glucose sensors stand out for their unique capabilities. While each method possesses its strengths, microwave sensors demonstrate commendable promise in providing real-time glucose data. The challenge now lies in refining these technologies collectively to meet the various requirements of individuals managing diabetes. Collaborative endeavours between engineers, medical professionals, and patients are crucial to achieving a holistic approach, ensuring not only technical excellence but also usability and clinical relevance. As we navigate the future landscape of glucose monitoring, the synthesis of microwave sensors with other non-invasive techniques holds potential for a comprehensive and effective approach. Through continuous research and collaborative initiatives, these innovations have the capacity to increase the value of life for individuals with diabetes, marking a substantial step onward in the evolution of non-invasive glucose level measuring technologies.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Kavyashree Puttananjegowda, Arash Takshi, Sylvia Thomas, An electrospun nanofibrous membrane based electrochemical glucose sensor, IEEE Sensors Letters 4 (2) (2020) 1–4.
[2] Pouya Saeedi, et al., Global and regional diabetes prevalence estimates for 2019 and projections for 2030 and 2045: results from the international diabetes federation diabetes atlas, Diabetes Res. Clin. Pract. 157 (2019) 107843.
[3] American Diabetes Association, Diagnosis and classification of diabetes mellitus, Diabetes Care 33 (Supplement_1) (2010) S62–S69.
[4] Fayssal Beloufa, Mohammed Amine Chikh, Design of fuzzy classifier for diabetes disease using Modified Artificial Bee Colony algorithm, Comput. Methods Progr. Biomed. 112 (1) (2013) 92–103.
[5] Nisan Ozana, et al., Noncontact speckle-based optical sensor for detection of glucose concentration using magneto-optic effect, J. Biomed. Opt. 21 (6) (2016), 065001-065001.
[6] U. Rajendra Acharya, et al., Automated identification of normal and diabetes heart rate signals using nonlinear measures, Comput. Biol. Med. 43 (10) (2013) 1523–1529.
[7] Kushal Sen Satish, Sneh Anand, Analysis of glucose-dependent dielectric properties of aqueous-based solution: a proof of concept, IET Sci. Meas. Technol. 15 (7) (2021) 562–568.
[8] David Rodbard, Continuous glucose monitoring: a review of recent studies demonstrating improved glycemic outcomes, Diabetes Technol. Therapeut. 19 (S3) (2017) S–25.
[9] Gojka Roglic, WHO Global report on diabetes: a summary, International Journal of Noncommunicable Diseases 1 (1) (2016).
[10] Danielle Bruen, et al., Glucose sensing for diabetes monitoring: recent developments, Sensors 17 (8) (2017) 1866.
[11] J. Comer, Semiquantitative specific test paper for glucose in urine, Anal. Chem. 28 (1956) 1748–1750.
[12] Huanfen Yao, et al., A contact lens with embedded sensor for monitoring tear glucose level, Biosens. Bioelectron. 26 (7) (2011) 3290–3296.
[13] Pietro R. Galassetti, et al., Breath ethanol and acetone as indicators of serum glucose levels: an initial report, Diabetes Technol. Therapeut. 7 (1) (2005) 115–123.
[14] Chuji Wang, Peeyush Sahay, Breath analysis using laser spectroscopic techniques: breath biomarkers, spectral fingerprints, and detection limits, Sensors 9 (10) (2009) 8230–8262.
[15] C. Wang, A. Mbi, M. Shepherd, A study on breath acetone in diabetic patients using a cavity ringdown breath analyzer: exploring correlations of breath acetone with blood glucose and glycohemoglobin A1C, IEEE Sens. J. 10 (2010) 54–63.
[16] Catherine Todd, et al., Towards non-invasive extraction and determination of blood glucose levels, Bioengineering 4 (4) (2017) 82.
[17] Danielle Bruen, et al., Glucose sensing for diabetes monitoring: recent developments, Sensors 17 (8) (2017) 1866.
[18] John L. Smith, The Pursuit of Noninvasive Glucose: Hunting the Deceitful turkey, Revised and Expanded, copyright, 2015.
[19] Danielle Bruen, et al., Glucose sensing for diabetes monitoring: recent developments, Sensors 17 (8) (2017) 1866.
[20] Stanley Kim, A pain-free Lancet with a small needle for Glucose Measurement, Clin. Med. Insights Endocrinol. Diabetes 3 (CMED-S3775) (2010).
[21] E. Amaied, R. Vargiolu, J.M. Bergheau, H. Zahouani, Aging Effect on Tactile Perception: Experimental and Modelling Studies, vols. 332–333, 2015 May, pp. 715–724.

[22] J. Hamilton, E. Ellinwood, Needle phobia: a neglected diagnosis, South. Med. J. 84 (Supplement) (1991) 27.

[23] T.-T. Wei, H.-Y. Tsai, C.-C. Yang, W.-T. Hsiao, K.-C. Huang, Noninvasive glucose evaluation by human skin oxygen saturation level, IEEE (2016) 1–5.

[24] A. Asaduzzaman, S. Samadarsinee, K.K. Chidella, “Simulating multisensor noninvasive blood glucose monitoring systems,”, SoutheastCon (2016) 1–7, 2016.

[25] A. Dehennis, S. Getzlaff, D. Grice, M. Mailand, An nfc enabled cmos ic for a wireless, fully implantable glucose sensor, Biomedical & Health Informatics IEEE Journal of 20 (1) (2016) 18–28.

[26] X.Y. Liu, Z.T. Wu, Y. Fan, M. Tentzeris, A miniaturized csrr loaded wide-beamwidth circularly polarized implantable antenna for subcutaneous real-time glucose monitoring, IEEE Antenn. Wireless Propag. Lett. 16 (2016) 577–580.

[27] N. Anabtawi, S. Freeman, R. Ferzli, A fully implantable, nfc enabled, continuous interstitial glucose monitor, IEEE (2016) 612–615.

[28] B. Lu, Y. Sun, X. Lai, Z. Pu, H. Yu, K. Xu, D. Li, Side-polished fiber spr sensor with tempetrature self-compensation for continuous glucose monitoring, IEEE (2016) 411–414.

[29] X. Wang, C. Mdingi, A. Dehennis, A.E. Colvin, Algorithm for an implantable fluorescence based glucose sensor, IEEE (2012) 3492–3495.

[30] Shang Wang, et al., Detection and monitoring of microparticles under skin by optical coherence tomography as an approach to continuous glucose sensing using implanted retroreflectors, IEEE Sensor. J. 13 (11) (2013) 4534–4541.

[31] Konrad Lorincz, et al., Sensor networks for emergency response: challenges and opportunities, IEEE pervasive Computing 3 (4) (2004) 16–23.

[32] Xian Huang, et al., A MEMS dielectric affinity glucose biosensor, J. Microelectromech. Syst. 23 (1) (2013) 14–20.

[33] Ebrahim Ghafar-Zadeh, et al., Toward implantable glucometer: design, modeling and experimental results. 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), IEEE, 2013.

[34] P. Dardano, et al., Diagnostic and therapeutic devices based on polymeric microneedles: fabrication and preliminary results. 2015 XVIII AISEM Annual Conference, IEEE, 2015.

[35] Stefania Guerra, et al., Enhancing the accuracy of subcutaneous glucose sensors: a real-time deconvolution-based approach, IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. 59 (6) (2012) 1658–1669.

[36] Haixia Yu, et al., An interstitial fluid transdermal extraction system for continuous glucose monitoring, J. Microelectromech. Syst. 21 (4) (2012) 917–925.

[37] X.Y. Liu, Z.T. Wu, Y. Fan, M. Tentzeris, A miniaturized csrr loaded wide-beamwidth circularly polarized implantable antenna for subcutaneous real-time glucose monitoring, IEEE Antenn. Wireless Propag. Lett. (2016) 577–580.

[38] Hyo Sang Yoon, Xuan Xing, Jae Yeong Park, Semi-implantable glucose sensor based on dual-stacked polymeric film for wireless continuous monitoring. 2016 IEEE 29th International Conference on Micro Electro Mechanical Systems (MEMS), IEEE, 2016.

[39] Sarah Ali Siddiqui, et al., Pain-free blood glucose monitoring using wearable sensors: recent advancements and future prospects, IEEE reviews in biomedical engineering 11 (2018) 21–35.

[40] N.A. Bazaev, I.P. Masloboev, S.V. Selishchev, Optical methods for noninvasive blood glucose monitoring, Med. Tekh. (2011) 29–33.

[41] Kai Takeuchi, Beomjoon Kim, Functionalized microneedles for continuous glucose monitoring, Nano convergence 5 (1) (2018) 28.

[42] Paolo Bollella, et al., Minimally invasive glucose monitoring using a highly porous gold microneedles-based biosensor: characterization and application in artificial interstitial fluid, Catalysts 9 (7) (2019) 580.

[43] Kwang Bok Kim, et al., Mussel-inspired enzyme immobilization and dual real-time compensation algorithms for durable and accurate continuous glucose monitoring, Biosens. Bioelectron. 143 (2019) 111622.

[44] Federico Ribet, Göran Stemme, Niclas Roxhed, Real-time intradermal continuous glucose monitoring using a minimally invasive microneedle-based system, Biomedical microdevices 20 (2018) 1–10.

[45] R.W. Waynant, V.M. Chenault, Overview of non-invasive fluid glucose measurement using optical techniques to maintain glucose control in diabetes mellitus, in: Overview of Non-invasive Optical Glucose Monitoring Techniques, IEEE Photonics Society, Piscataway, NJ, 1998.

[46] Chi-Fuk So, et al., Recent advances in noninvasive glucose monitoring, Medical devices (Auckland, N.Z 5 (2012) 45–52.

[47] H. Michael Heise, Sven Delbeck, Ralf Marbach, Noninvasive monitoring of glucose using near-infrared reflection spectroscopy of skin—constraints and effective novel strategy in multivariate calibration, Biosensors 11 (3) (2021) 64.

[48] Michael Hlavatsch, Boris Mizaikoff, Advanced mid-infrared lightsources above and beyond lasers and their analytical utility, Anal. Sci. 38 (9) (2022) 1125–1139.

[49] Wenwen Zhang, et al., A review of machine learning for near-infrared spectroscopy, Sensors 22 (24) (2022) 9764.

[50] Bushra Alsunaidi, et al., A review of non-invasive optical systems for continuous blood glucose monitoring, Sensors 21 (20) (2021) 6820.

[51] Guang Han, et al., Noninvasive blood glucose sensing by near-infrared spectroscopy based on PLSR combines SAE deep neural network approach, Infrared Phys. Technol. 113 (2021) 103620.

[52] Tongshuai Han, et al., In vivo near-infrared noninvasive glucose measurement and detection in humans, Appl. Spectrosc. 76 (9) (2022) 1100–1111.

[53] Murad Althobaiti, "In silico investigation of SNR and dermis sensitivity for optimum dual-channel near-infrared glucose sensor designs for different skin colors.", Biosensors 12 (10) (2022) 805.

[54] Ruochong Zhang, et al., Noninvasive electromagnetic wave sensing of glucose, Sensors 19 (5) (2019) 1151.

[55] Kazi Atique Moula Nabil, et al., Development of A Smart non-invasive glucose monitoring system with SpO2 and BPM for diabetic patient, in: 2023 IEEE 13th Annual Computing and Communication Workshop and Conference (CCWC), IEEE, 2023.

[56] Gonzales Villena, Ahmed Toaha Mobashsher Wilbert, Abbosh Amin, The progress of glucose monitoring—a review of invasive to minimally and non-invasive techniques, devices and sensors, Sensors 19 (4) (2019) 800.

[57] Kasun D. Pathirage, et al., Removing subject dependencies on non-invasive blood glucose measurement using hybrid techniques, in: Proceedings of the 2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC, Berlin, Germany, 23–27 July 2019.

[58] Tomoya Kitazaki, et al., Glucose emission spectra through mid-infrared passive spectroscopic imaging of the wrist for non-invasive glucose sensing, Sci. Rep. 12 (1) (2022) 20558.

[59] M. Althobaiti, Estimation of the differential pathlength factor for human skin using Monte Carlo simulations, Diagnostics 13 (2023) 309.

[60] Z. Tang, S.J. Barton, T.E. Ward, J.P. Lowry, M.M. Doran, H.J. Byrne, B.M. Hennelly, Multicomponent analysis using a confocal Raman microscope, Appl. Opt. 57 (2018) E118–E130.

[61] D. Yang, S. Afroosheh, J.O. Lee, H. Cho, S. Kumar, R.H. Siddique, V. Narasimhan, Y.Z. Yoon, A.T. Zayak, H. Choo, Glucose sensing using surface-enhanced Raman-mode constraining, Anal. Chem. 90 (2018) 14269–14278.

[62] J. Shao, M. Lin, Y. Li, X. Li, J. Liu, J. Liang, H. Yao, In vivo blood glucose quantification using Raman spectroscopy, PLoS One 7 (2012) e48127.

[63] W. Villena Gonzales, A. Mobashsher, A. Abbosh, The progress of glucose monitoring—a review of invasive to minimally and non-invasive techniques, devices and sensors, Sensors 19 (4) (Feb. 2019).

[64] S. Meyhöfer, et al., Evaluation of a near-infrared light ultrasound system as a non-invasive blood glucose monitoring device, Diabetes Obes. Metabol. 22 (4) (Apr. 2020) 694–698.

[65] E.-Y. Park, J. Baik, H. Kim, S.-M. Park, C. Kim, Ultrasound-modulated optical glucose sensing using a 1645 nm laser, Sci. Rep. 10 (1) (Dec. 2020).

[66] A. Srivastava, M. Chowdhury, S. Sharma, N. Sharma, In-vitro measurement of glucose concentration in human blood plasma mixed intralipid phantom samples by using modulated ultrasound and infrared light, Br. Biotechnol. J. 13 (1) (Jan. 2016) 1–14.

[67] T. Kitazaki, et al., Parametric standing wave generation of a shallow reflection plane in a nonrigid sample for use in a noninvasive blood glucose monitor, J. Biomed. Opt. 24 (3) (Mar. 2019).

[68] J.C. Pickup, F. Hussain, N.D. Evans, O.J. Rolinski, D.J. Birch, Fluorescence-based glucose sensors, Biosens. Bioelectron. 20 (12) (2005) 2555–2565.

[69] O.S. Khalil, Noninvasive photonic-crystal material for sensing glucose in tears, Clin. Chem. 50 (12) (2004) 2236–2237.

[70] E.A. Moschou, B.V. Sharma, S.K. Deo, S. Daunert, Fluorescence glucose detection: advances toward the ideal in vivo biosensor, J. Fluoresc. 14 (5) (2004) 535–547.

[71] H. Lee, C. Song, Y.S. Hong, M.S. Kim, H.R. Cho, T. Kang, K. Shin, S.H. Choi, T. Hyeon, D.H. Kim, Wearable/disposable sweat-based glucose monitoring device with multistage transdermal drug delivery module, Sci. Adv. 3 (2017) e1601314.

[72] Q. Zhai, S. Gong, Y. Wang, Q. Lyu, Y. Liu, Y. Ling, J. Wang, G.P. Simon, W. Cheng, Enokitake mushroom-like standing gold nanowires toward wearable noninvasive bimodal glucose and strain sensing, ACS Appl. Mater. Interfaces 11 (2019) 9724–9729.

[73] W. Gao, H. Ota, D. Kiriya, K. Takei, A. Javey, Flexible electronics toward wearable sensing, Acc. Chem. Res. 52 (2019) 523–533.

[74] A.J. Bandodkar, P. Gutruf, J. Choi, K. Lee, Y. Sekine, J.T. Reeder, W.J. Jeang, A.J. Aranyosi, S.P. Lee, J.B. Model, et al., Battery-free, skin-interfaced microfluidic/electronic systems for simultaneous electrochemical, colorimetric, and volumetric analysis of sweat, Sci. Adv. 5 (2019) eaav3294.

[75] J. Kim, J.R. Sempionatto, S. Imani, M.C. Hartel, A. Barfidokht, G. Tang, A.S. Campbell, P.P. Mercier, J. Wang, Simultaneous monitoring of sweat and interstitial fluid using a single wearable biosensor platform, Adv. Sci. 5 (2018) 1800880.

[76] M. Gourzi, A. Rouane, R. Guelaz, et al., Non-invasive glycaemia blood measurements by electromagnetic sensor: study in static and dynamic blood circulation, J. Med. Eng. Technol. 29 (1) (2005) 22–26.

[77] A. Tura, S. Sbrignadello, D. Cianciavicchia, G. Pacini, P. Ravazzani, A low frequency electromagnetic sensor for indirect measurement of glucose concentration: in vitro experiments in different conductive solutions, Sensors 10 (6) (2010) 5346–5358.

[78] G.R. Moran, K.R. Jeffrey, J.M. Thomas, J.R. Stevens, A dielectric analysis of liquid and glassy solid glucose/water solutions, Carbohydr. Res. 328 (4) (2000) 573–584.

[79] H. Melikyan, E. Danielyan, S.W. Kim, et al., Non-invasive in vitro sensing of D-glucose in pig blood, Med. Eng. Phys. 34 (3) (2012) 299–304.

[80] S.A. Weinzimer, Analysis: pendra: the once and future noninvasive continuous glucose monitoring device? Diabetes Technol. Ther 6 (2004) 442–444.

[81] A. Caduff, E. Hirt, Y. Feldman, Z. Ali, L. Heinemann, First human experiments with a novel non-invasive, non-optical continuous glucose monitoring system, Biosens. Bioelectron. 19 (3) (2003) 209–217.

[82] A. Caduff, M.S. Talary, M. Mueller, et al., Non-invasive glucose monitoring in patients with Type 1 diabetes: a multisensor system combining sensors for dielectric and optical characterisation of skin, Biosens. Bioelectron. 24 (9) (2009) 2778–2784.

[83] T. Yilmaz, R. Foster, Y. Hao, Radio-frequency and microwave techniques for non-invasive measurement of blood glucose levels, Diagnostics 9 (2019) 6.

[84] V. Turgul, I. Kale, Permittivity extraction of glucose solutions through artificial neural networks and non-invasive microwave glucose sensing, Sens. Actuators A Phys. 277 (2018) 65–72.

[85] A.E. Omer, G. Shaker, S. Safavi-Naeini, H. Kokabi, G. Alquié, F. Deshours, R.M. Shubair, Low-cost portable microwave sensor for non-invasive monitoring of blood glucose level: novel design utilizing a four-cell CSRR hexagonal configuration, Sci. Rep. 10 (2020) 15200.

[86] J. Hanna, Y. Tawk, S. Azar, A.H. Ramadan, B. Dia, E. Shamieh, S. Zoghbi, R. Kanj, J. Costantine, A.A. Eid, Wearable flexible body matched electromagnetic sensors for personalized non-invasive glucose monitoring, Sci. Rep. 12 (2022) 14885.

[87] T. Yilmaz, R. Foster, Y. Hao, Radio-frequency and microwave techniques for non-invasive measurement of blood glucose levels, Diagnostics 9 (2019) 6.

[88] R. Zhang, S. Liu, H. Jin, Y. Luo, Z. Zheng, F. Gao, Y. Zheng, Noninvasive electromagnetic wave sensing of glucose, Sensors 19 (2019) 1151.

[89] W. Villena Gonzales, A.T. Mobashsher, A. Abbosh, The progress of glucose monitoring-A review of invasive to minimally and non-invasive techniques, devices and sensors, Sensors 19 (2019) 800.

[90] V. Turgul, I. Kale, Simulating the effects of skin thickness and fingerprints to highlight problems with non-invasive RF blood glucose sensing from fingertips, IEEE Sens. J. 17 (2017) 7553–7560.

[91] M. Hofmann, G. Fischer, R. Weigel, D. Kissinger, Microwave-based noninvasive concentration measurements for biomedical applications, IEEE Trans. Microw. Theory Tech. 61 (2013) 2195–2204.

[92] H. Choi, S. Luzio, J. Beutler, A. Porch, Microwave noninvasive blood glucose monitoring sensor: penetration depth and sensitivity analysis, in: Proceedings of the 2018 Ieee/Mtt-S International Microwave Biomedical Conference, Imbioc), Philadelphia, PA, USA, 2018, pp. 52–54, 14–15 June.

[93] S. Gabriel, R.W. Lau, C. Gabriel, The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues, Phys. Med. Biol. 41 (1996) 2271–2293.

[94] C. Jang, J.-K. Park, H.-J. Lee, G.-H. Yun, J.-G. Yook, Non-invasive fluidic glucose detection based on dual microwave complementary split ring resonators with a switching circuit for environmental effect elimination, IEEE Sens. J. 20 (2020) 8520–8527.

[95] P.S. Hall, Y. Hao, Antennas and Propagation for Body-Centric Wireless Networks, first ed., Artech House, Norwood, MA, USA, 2006. ISBN 1-58053-493-7.

[96] C. Gabriel, S. Gabriel, E. Corthout, The dielectric properties of biological tissues: I. Literature survey, Phys. Med. Biol. 41 (1996) 2231–2249.

[97] S. Gabriel, R. Lau, C. Gabriel, The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz, Phys. Med. Biol. 41 (1996) 2251–2269.

[98] S. Gabriel, et al., The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues, Phys. Med. Biol. 41 (11) (1996) 2271–2293.

[99] Mariya Lazebnik, et al., A large-scale study of the ultrawideband microwave dielectric properties of normal, benign and malignant breast tissues obtained from cancer surgeries, Phys. Med. Biol. 52 (20) (2007) 6093–6115.

[100] Onan Güren, et al., Surface impedance based microwave imaging method for breast cancer screening: contrast-enhanced scenario, Phys. Med. Biol. 59 (19) (2014) 5725.

[101] R.W. Paglione, Coaxial applicator for microwave hyperthermia, U.S. Patent 4 (204) (27 May 1980) 549.

[102] L. Dean, Blood and the cells it contains, in: Blood Groups and Red Cell Antigens, National Center for Biotechnology Information (US), Bethesda, MD, USA, 2005.

[103] K. Zirk, H. Poetzschke, On the suitability of refractometry for the analysis of glucose in blood-derived fluids, Med. Eng. Phys. 26 (2004) 473–481.

[104] E. Cengiz, W.V. Tamborlane, A tale of two compartments: interstitial versus blood glucose monitoring, Diabetes Technol. Ther. 11 (2009). S-11–S-16.

[105] V. Turgul, I. Kale, Simulating the effects of skin thickness and fingerprints to highlight problems with non-invasive RF blood glucose sensing from fingertips, IEEE Sens. J. 17 (2017) 7553–7560.

[106] M. Karami, P. Rezaei, S. Kiani, R.A. Sadeghzadeh, Modified planar sensor for measuring dielectric constant of liquid materials, Electron. Lett. 53 (19) (2017) 1300–1302.

[107] A.E. Omer, S. Gigoyan, G. Shaker, S. Safavi-Naeini, WGM-based sensing of characterized GlucoseAqueous solutions at mm-waves, IEEE Access 8 (2020) 38809–38825.

[108] J. Vrba, J. Karch, D. Vrba, Phantoms for development of microwave sensors for noninvasive blood glucose monitoring, Int. J. Antennas Propag. (2015, 2015) 1–5.

[109] S. Kim, H. Melikyan, J. Kim, A. Babajanyan, J.H. Lee, L. Enkhtur, B. Friedman, K. Lee, Noninvasive in vitro measurement of pig-blood d-glucose by using a microwave cavity sensor, Diabetes Res. Clin. Pract. 96 (2012) 379–384.

[110] Andrey Zapasnoy, et al., Interaction of the near-field microwave wideband sensor with biological tissues for glucose monitoring. 2020 IEEE MTT-S International Microwave Biomedical Conference (IMBioC), IEEE, 2020.

[111] Joséphine Masini, et al., Penetration depth in multilayered biological tissues using a compact microwave biosensor. 2022 52nd European Microwave Conference (EuMC), IEEE, 2022.

[112] Sina Kiani, Pejman Rezaei, Microwave substrate integrated waveguide resonator sensor for non-invasive monitoring of blood glucose concentration: low cost and painless tool for diabetics, Measurement 219 (2023) 113232.

[113] T. Yilmaz, R. Foster, Y. Hao, Towards accurate dielectric property retrieval of biological tissues for blood glucose monitoring, IEEE Trans. Microw. Theory Tech. 62 (2014) 3193–3204.

[114] Carlos G. Juan, et al., On the selectivity of planar microwave glucose sensors with multicomponent solutions, Electronics 12 (1) (2022) 191.

[115] Supakorn Harnsoongnoen, Benjaporn Buranrat, Advances in a microwave sensor-type interdigital capacitor with a hexagonal complementary split-ring resonator for glucose level measurement, Chemosensors 11 (4) (2023) 257.

[116] Heungjae Choi, et al., Design and in vitro interference test of microwave noninvasive blood glucose monitoring sensor, IEEE Trans. Microw. Theor. Tech. 63 (10) (2015) 3016–3025.

[117] Levon Odabashyan, et al., Real-time noninvasive measurement of glucose concentration using a modified Hilbert shaped microwave sensor, Sensors 19 (24) (2019) 5525.

[118] Chorom Jang, et al., Temperature-corrected fluidic glucose sensor based on microwave resonator, Sensors 18 (11) (2018) 3850.

[119] Giovanni Buonanno, et al., Response sharpening of resonant sensors for potential applications in blood glucose monitoring, IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology 6 (2) (2022) 287–293.

[120] Muhammad Farhan Affendi Mohamad Yunos, et al., RF remote blood glucose sensor and a microfluidic vascular phantom for sensor validation, Biosensors 11 (12) (2021) 494.

[121] Mohammad Tariqul Islam, et al., Left-handed metamaterial-inspired unit cell for S-Band glucose sensing application, Sensors 19 (1) (2019) 169.

[122] Carlos G. Juan, et al., On the selectivity of planar microwave glucose sensors with multicomponent solutions, Electronics 12 (1) (2022) 191.

[123] Louis WY. Liu, et al., Non-invasive blood glucose monitoring using a curved Goubau line, Electronics 8 (6) (2019) 662.

[124] Igbe Tobore, et al., Deep learning intervention for health care challenges: some biomedical domain considerations, JMIR mHealth and uHealth 7 (8) (2019) e11966.

[125] Tobore Igbe, et al., Analysis of ECG segments for non-invasive blood glucose monitoring. 2019 IEEE International Conference on E-Health Networking, Application & Services (HealthCom), IEEE, 2019.

[126] Igbe Tobore, et al., Statistical and spectral analysis of ECG signal towards achieving non-invasive blood glucose monitoring, BMC Med. Inf. Decis. Making 19 (2019) 1–14.

[127] Louis WY. Liu, et al., In-vivo and ex-vivo measurements of blood glucose using whispering gallery modes, Sensors 20 (3) (2020) 830.

[128] Abhishek Kandwal, Zedong Nie, Hao Yang, Using highly confined fields to develop biosensors for glucose measurements. 2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, IEEE, 2020.

[129] Jingzhen Li, et al., A novel CGM metric-gradient and combining mean sensor glucose enable to improve the prediction of nocturnal hypoglycemic events in patients with diabetes, J. Diabetes Res. 2020 (2020).

[130] Jingzhen Li, et al., Non-invasive monitoring of three glucose ranges based on ECG by using DBSCAN-CNN, IEEE journal of biomedical and health informatics 25 (9) (2021) 3340–3350.

[131] Abhishek Kandwal, et al., A novel method of using bifilar spiral resonator for designing thin robust flexible glucose sensors, IEEE Trans. Instrum. Meas. 70 (2021) 1–10.

[132] Jingzhen Li, et al., Towards noninvasive and fast detection of Glycated hemoglobin levels based on ECG using convolutional neural networks with multisegments fusion and Varied-weight, Expert Syst. Appl. 186 (2021) 115846.

[133] Jingzhen Li, et al., Gradient variability coefficient: a novel method for assessing glycemic variability and risk of hypoglycemia, Endocrine 76 (1) (2022) 29–35.

[134] Abhishek Kandwal, et al., Designing highly sensitive microwave antenna sensor with novel model for noninvasive glucose measurements, Prog. Electromagn. Res. 176 (2023) 129–141.

[135] Tobore Igbe, et al., Inspection of EEG signals for noninvasive blood glucose monitoring in prediabetes diagnosis. 2023 IEEE International Symposium on Medical Measurements and Applications (MeMeA), IEEE, 2023.

[136] Mandeep Chhajer Jain, et al., Differential microwave resonator sensor reveals glucose-dependent growth profile of E. coli on solid agar, IEEE Microw. Wireless Compon. Lett. 30 (5) (May 2020).

[137] S. Wang, W. Wang, Y. Zheng, Reconfigurable multimode microwave sensor with resonance and transmission sensing capabilities for noninvasive glucose monitoring, IEEE Trans. Microw. Theor. Tech. 72 (5) (May 2024) 3102–3117.

[138] Z. Wang, X. Xiao, Y. Pang, W. Su, T. Kikkawa, Noninvasive, intelligent blood glucose monitoring on fingertip using dual-band fusion and LSTM-R network, IEEE Sensor. J. 24 (3) (2024) 3465–3476.

[139] Esraa Mansour, et al., A microwave sensor based on double complementary split-ring resonator using hexagonal configuration for sensing diabetics glucose levels. 2023 17th European Conference on Antennas and Propagation (EuCAP), IEEE, 2023.

[140] S. Kiani, P. Rezaei, M. Fakhr, Investigation of microwave resonant sensors for use in detecting changes of non-invasive blood glucose concentration. Organic and Inorganic Materials Based Sensors, 3 Volumes, Wiley, 2024, pp. 1055–1064.

[141] Woo Haneul, Lee Hee-Jo, Yook Jong-Gwan, Non-invasive detection of glucose and NaCl solutions with environment correction using a dual IDC-based microwave sensor, IEEE Sensor 11 (12) (2024) 19039–19049.

[142] Chih-Yu Chang, Hsiao-Chin Chen, CMOS transmitter and PCB probe for MMW-transmission-based glucose sensors, IEEE Sensor. 24(7) J. (2024) 9375–9382.

[143] Sina Kiani, et al., Band-stop filter sensor based on SIW cavity for the non-invasive measuring of blood glucose, IET Wirel. Sens. Syst. 9 (Issue 1) (2019) 1–5.

[144] Sina Kiani, Pejman Rezaei, Moein Navaei, Dual-sensing and dual-frequency microwave SRR sensor for liquid samples permittivity detection, Measurement 160 (2020) 107805.

[145] N. Nikkhah, R. Keshavarz, M. Abolhasan, J. Lipman, N. Shariati, Highly sensitive differential microwave sensor using enhanced spiral resonators for precision permittivity measurement, IEEE Sensor. J. 24 (9) (2024) 14177–14188, 1 May1.

[146] Ala Eldin Omer, et al., Low-cost portable microwave sensor for non-invasive monitoring of blood glucose level: novel design utilizing a four-cell CSRR hexagonal configuration, Sci. Rep. 10 (1) (2020) 15200.

[147] S. Kiani, P. Rezaei, M. Fakhr, Dual-frequency microwave resonant sensor to detect non-invasive glucose-level changes through the fingertip, IEEE Trans. Instrum. Meas. 70 (2021) 1–8. Art no. 6004608.

[148] S. Kiani, P. Rezaei, M. Fakhr, Real-time measurement of liquid permittivity through label-free meandered microwave sensor, IETE J. Res. 1–11 (2023).