Glucose Detection Using Patch Antennas

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Abstract:

There's a significant demand for highly sensitive and reliable biosensors that do not rely on labeling, which has sparked extensive research into creating small-scale radio frequency resonators for various biomedical uses. In this study, a sturdy and reusable biosensor is created using an integrated passive radio frequency device called a patch antenna, for glucose detection in a simulated serum sample. The values obtained from the simulated S-parameter measurements include, the magnitude and the angle for S11(input reflection), S21(gain/loss/thru), S12(insertion loss), and S22(output reflection). Other measurement values include the systems capacitance, inductance, resistance, and its propagation constant. All of these measurement parameters allow for the effective detection of glucose levels within a blood sample.

The journey towards efficient glucose monitoring began in the 1970s with the introduction of the Dextrostix glucose meter. However, its precision and reliability were subpar. By the mid-1970s, the idea of home-based patient blood glucose monitoring started gaining traction, leading to the launch of the Dextrometer in 1980. This device combined the Dextrostix with a digital display for better user experience. In the 1980s, there was significant progress in the development of glucose meters and strips that required smaller blood samples and were more affordable. Self-monitoring of blood glucose (SMBG) soon became a standard care practice, particularly for individuals living with type 1 diabetes. This progress, alongside the advent of A1C testing and insulin pump therapy, paved the way for the Diabetes Control and Complications Trial. This trial conclusively proved the long-suspected link between effective glucose control and the management of diabetes-related complications [1].

A patch antenna, which is also commonly referred to as a microstrip antenna, is a type of radio antenna typically characterized by its low-profile design. It is comprised of a flat metallic piece and the shape of it can vary, that sits over a larger metal sheet known as the ground plane. Usually, this assembly is encased in plastic for protection. The patch and the ground plane have a dielectric material, known as the substrate, sandwiched between them. In certain designs, more than one patch might be used. The resonant frequency of the patch antenna is influenced by the size and shape of the patch, the nature of the substrate material, and the distance separating the patch and the ground plane. The radiation pattern, or how the antenna broadcasts and receives signals, can be altered by adjusting the physical aspects of the antenna, such as its form, size, and the dielectric properties of the substrate. Patch antennas are highly valued for their slim profile and the ease with which they can be manufactured, leading to their wide usage across products and industries [2].
Introduction:

Diabetes is a metabolic ailment categorized by the variations in blood glucose levels beyond the standard range of a typical patient. This fluctuation is due to either insufficient production (type 1) or inefficient usage (type 2) of the hormone insulin. This multifaceted disease can potentially impact every organ in the body, leading to complications like blindness, kidney failure, heart disease, and nerve damage. According to the World Health Organization (WHO), diabetes was the seventh leading cause of death globally in 2016, and the International Diabetes Federation estimated that nearly 4.2 million people died due to diabetes-related complications in 2019, and this number is rapidly growing [3]. Thus, managing diabetes remains a to be a massive world challenge.

One study showed that a sequential escalation in these complications occurs as blood glucose levels rise from the standard fasting plasma glucose level of 0.89 mg/mL to levels beyond 3.5 mg/mL [4]. However, these complications can be prevented by meticulously and accurately tracking blood glucose levels using a biosensor. When blood glucose levels deviate, they can be managed with suitable actions such as diet modifications, physical activity, insulin injections, or oral medication. Research into developing glucose biosensors continues to avert severe health risks and the debilitating complications linked to diabetes. Various glucose biosensors have been developed using different transduction methods, but mostly consisting of a variety of electrochemical biosensors. Electrochemical biosensors, especially non-enzymatic ones, are the most commonly used for sensitive glucose detection, designed to counteract degradation caused by mediators in enzymatic glucose sensors. However, their performance is hampered by interference from inconsistencies in the dialectic substrate as well as in the sample medium.

Recently, reports have emerged on the use of radio frequency (RF)-based biosensors that do not require labeling for various applications. These applications range from detecting stress biomarkers, observing biomolecular binding, performing human cell dielectric spectroscopy, to detecting glucose. These glucose sensors work by evaluating electromagnetic coupling levels that are determined by the permittivity of glucose, which in turn is influenced by the local glucose concentration. These are all classified as different variations of glucose sensors, but they offer similar the benefits of quick turnaround times in the lab and the accurate detection of glucose. However, despite these benefits, there remain certain issues affecting the precision and sensitivity of this technology. This proof-of-concept simulation is aimed to create a small, reusable biosensor based on a patch antenna system for detecting glucose without a mediator in both a deionized water solution or an empty container with high sensitivity as a calibration medium and simulated human serum as the measurement medium. A resonator known as a patch antenna, with a central frequency that is suitable for sensitive glucose detection was constructed.

Similar research into RF glucose sensors have used cavity type glucose methods that are based on using the resonance frequency of the cavity and the sample for measurements. Microwave cavity perturbation theory is a commonly applied technique that enables the precise measurement of a material's electrical properties. When a dielectric material is introduced into a microwave cavity, it alters the resonant frequency within that cavity. Since varying
concentrations of glucose solutions each have unique electrical characteristics, changes in the cavity's properties can be used to estimate their glucose concentration. This estimation process employs the microwave cavity perturbation approach [5]. Other methods have used shaped microstrip transmission lines to form standing waves as a measurement. Essentially, the resonator in question is a microstrip transmission line designed in a spiral shape, equipped with two ports. These ports are capacitively coupled to two straight microstrip lines running along the spiral line. The spiral design was chosen due to its symmetry, which helps in reducing errors related to contact orientation, and its ability to create a standing wave. The strength of this standing wave was monitored by measuring the amplitude of S21 [6]. And on an even more basic level tradition glucose sensors have been implemented with RF transmitters for active monitoring. Radio frequency identification (RFID) technology presents the opportunity to transmit data from glucose monitors to an external device without requiring invasive measures like wires or other forms of direct contact. Currently, both implantable and non-invasive glucose monitors incorporating RFID technology are in the stages of development [7].

The simulation results demonstrated here show a clear detection of the shift in the resonator's center frequency by a sharp S11 for different glucose concentrations, confirming the possibility of high-sensitivity glucose detection. The changes that occur in the magnitude of the S11 at Fc (the center frequency) and the changes of S21 based off of the calibration plane were utilized to improve detection accuracy.

Simulation:

The simulation process was performed using the High Frequency Structure Simulator (HFSS) software. HFSS is a 3D electromagnetic (EM) simulation software that uses finite element methods to accurately solve complex problems and provide precise predictions of EM field behavior. This software has been particularly effective for designing and simulating high-frequency electronic products such as antennas, RF or microwave components, and high-speed interconnects. The patch antenna was designed utilizing a Rogers RO3035 substrate. This substrate was chosen because of its beneficial properties like its relative permittivity of 3.5, which is apt for this application, and a low loss tangent of 0.0013 at 10 GHz. The substrate also exhibits low thermal expansion for reliability in varying thermal conditions, which is a crucial parameter for the sensor operation. The patch antenna was constructed from a 1/2-ounce gold material with a thickness of 0.7 mils. Gold was selected as the patch material due to its high electrical conductivity and corrosion resistance, providing good antenna performance and longevity. The final dimensions of the antenna were determined through several iterations of design and simulation, ensuring that the desired frequency range was achieved.
The patch antenna was then duplicated and placed above the original, creating a space in between for sample insertion. This configuration forms a resonant cavity, with the top and bottom patch antennas behaving as the two plates of a capacitor. The electromagnetic field in this cavity interacts with the sample placed within, causing changes in the antenna’s resonant frequency that can be measured. The sample container was designed using Teflon due to its extremely low dielectric constant and loss tangent, thereby minimally affecting the EM field between the patch antennas. This design allows the container to hold the blood sample without significantly interfering with the resonance of the antenna system. In the simulation, the blood
sample's dielectric constant was set as a variable. The dielectric constant was then swept within the typical range for blood with varying glucose levels. The resulting shift in the resonant frequency of the patch antenna due to this sweep was observed, simulating the effect of different glucose concentrations in the blood sample.

*Figure 3: Data used for the Dielectric Constant Value ($\varepsilon_r$) Sweep vs Glucose Level:*

![Graphs showing dielectric constant sweep vs glucose level](image)

*Figure 4: Setting up the Patch Antenna System with Teflon container and sample medium:*

![Diagram of patch antenna system](image)
Figure 5: Top-down view:

Figure 6: Side View:
By correlating the shift in resonant frequency with the glucose concentration, the proposed patch antenna system demonstrated its potential as a non-invasive method for measuring blood glucose levels. Further analysis and physical testing are needed to validate these simulation results and refine the system's sensitivity and accuracy. The development of an algorithm to interpret the shifts in resonant frequency into accurate glucose level readings will need to be part of ongoing future research efforts. This simulation model allowed the investigating of the proposed system's capabilities in a controlled environment and assists in identifying potential design modifications for performance optimization. It sets the foundation for the empirical testing phase of the project, where it can correlate the simulation findings with real-world data.

**System Simulation Data with Sample $\varepsilon_r$ Value Swept:**

*Figure 7: Input Return Loss ($S_{11}$) and Thru ($S_{21}$) Measurements:*
Methods:

The methodology of this study can be divided into three distinct stages: antenna design, simulation setup, and dielectric constant sweep. Each stage was executed using High Frequency Structure Simulator (HFSS), a leading tool for simulating high-frequency electronic products. The antenna system was constructed using a Rogers RO3035 substrate due to its beneficial electrical and thermal properties. The substrate was chosen for its relative permittivity of 3.5 and low loss tangent of 0.0013 at 10 GHz. These properties are critical in ensuring effective antenna performance and accurate simulation results. The patch antenna was designed using a 1/2 ounce gold material with a thickness of 0.7 mils. Gold was selected for its high electrical conductivity and corrosion resistance, which are beneficial for effective antenna performance and longevity. The patch antenna was then duplicated and positioned over the original, thereby creating a gap for sample placement. This gap is crucial as it forms a resonant cavity where the electromagnetic field interacts with the blood sample.

The simulation was performed using HFSS, which relies on finite element methods to solve complex EM problems and deliver precise predictions. The duplicated patch antenna design was imported into the software and a simulation space was defined around it. A Teflon container, owing to its low dielectric constant and loss tangent, was modeled to hold the blood sample. The blood sample’s dielectric constant was set as a variable within the simulation. The constant was then swept within the typical range for blood with varying glucose levels, which allowed the observation of the resulting shift in the resonant frequency of the patch antenna. Through this method, the effect of different glucose concentrations on the antenna's resonant frequency was successfully simulated. This provided the foundation for the development of a
non-invasive technique for measuring blood glucose levels, where shifts in the resonant frequency could be correlated with varying glucose concentrations.

Then to validate the simulation results, the testing and refining of the antenna design to optimize its performance is required. The development of an algorithm to convert the shifts in resonant frequency into accurate glucose level readings will need to be finalized as well. This method of simulation and analysis demonstrates the potential of patch antenna systems in biomedical diagnostics, paving the way for further advancements in non-invasive glucose monitoring technology.

Results:

Following the simulation of the proposed patch antenna system using HFSS, it was observed several key findings that underscore its potential for non-invasive blood glucose level measurement. The varying dielectric constant of the blood sample, which was set as a variable in the simulation to represent different glucose concentrations, led to discernible shifts in the resonant frequency of the antenna. Specifically, as the dielectric constant increased, indicating a rise in glucose concentration, the resonant frequency of the antenna system demonstrated a proportional decrease. This negative correlation between the dielectric constant and the resonant frequency of the antenna is consistent with electromagnetic theory, further validating the system's theoretical design. Additionally, it can be noted that the antenna's frequency shift due to variations in the dielectric constant of the sample was within a manageable range for typical RF electronics. This ensures the practical feasibility of the proposed system for glucose level measurement, as the frequency shifts can be accurately measured with standard RF equipment. The substrate material, Rogers RO3035, performed well in the simulations, offering a stable platform for the patch antenna. The gold patch material also provided the necessary conductivity for optimal antenna performance. The Teflon container, owing to its low dielectric constant, did not significantly interfere with the electromagnetic field in the cavity, ensuring that the changes in resonant frequency were predominantly influenced by the sample.

The simulation model demonstrated a robust and linear relationship between the blood glucose level and the resonant frequency of the patch antenna. This direct correlation presents an opportunity to develop an algorithm to translate the resonant frequency shifts into accurate blood glucose level readings. However, it is important to note that these findings represent ideal conditions within a controlled simulation environment. Real-world scenarios will introduce additional complexities, including blood composition variations beyond glucose concentration, temperature effects, and potential interference. Further refinement of the antenna system design and extensive empirical testing are needed to validate these simulation results and adjust for these variables. In conclusion, the simulation results strongly indicate that the proposed patch antenna system, designed with Rogers RO3035 substrate and gold patch material, could provide a reliable non-invasive means of measuring blood glucose levels. The success of this project opens doors for further research into other applications of patch antenna systems in biomedical diagnostics.
Discussion:

This research leverages the powerful capabilities of High Frequency Structure Simulator (HFSS) software to develop a non-invasive glucose monitoring system. The engineered patch antenna system based on a Rogers RO3035 substrate and a gold patch antenna, designed to interact with a blood sample to determine glucose levels based on electromagnetic principles. The Rogers RO3035 was specifically chosen as the substrate material due to its ideal dielectric constant and low loss tangent. The choice of gold as the patch material aligns with its excellent conductivity and corrosion resistance, thereby ensuring consistent and robust antenna performance over time. Both materials have proven to perform as expected in the simulations, providing a solid platform for the patch antenna design. The model included a second patch antenna placed above the original, creating a resonant cavity where the electromagnetic field interacts with the blood sample. The use of a Teflon container to encapsulate the sample proved instrumental in minimizing interference with the electromagnetic field due to its extremely low dielectric constant and loss tangent.

During the simulation, the blood sample's dielectric constant was varied to represent the range of potential glucose levels. The resonant frequency of the patch antenna system showed a noticeable shift in response to these changes. More specifically, the resonant frequency decreased as the dielectric constant, corresponding to an increased glucose level, rose. This negative correlation reflects the expected behavior as per electromagnetic theory, thereby reinforcing the theoretical basis of the system design. An encouraging aspect of the simulation results is that the resonant frequency shift fell within the operational range of typical RF electronics. This ensures that the system is not just theoretically sound, but also practically feasible. Standard RF equipment should be capable of accurately measuring these shifts, thereby simplifying the hardware requirements of the system. However, it is essential to remember that the results obtained are from a controlled simulation environment. Real-world scenarios will inevitably introduce additional variables that the simulation did not account for. These may include other constituents in blood that could affect the dielectric constant, fluctuations in physiological temperature, and electromagnetic interference from nearby devices. Thus, comprehensive empirical testing is required to validate and refine the simulation results to improve the system's accuracy and reliability in real-world settings.

Moving forward, a significant task will be to develop an accurate algorithm to convert the observed shifts in the resonant frequency into glucose level readings. The linear relationship observed in the simulations between the dielectric constant (representing glucose concentration) and resonant frequency shift provides a promising basis for this algorithm. The results from this study highlight the tremendous potential of patch antenna systems in biomedical diagnostics. The proposed design demonstrates the possibility of using patch antennas for non-invasive glucose monitoring, a much-needed advancement in diabetes management. Future work will focus on the empirical validation of these findings, the development of an accurate translation algorithm, and adjustments to the antenna design to accommodate real-world conditions and challenges. This
research serves as an essential stepping stone towards a more patient-friendly and efficient method of glucose monitoring.
Author Information:

Joshua Paul Joseph is currently pursuing a Master's degree in Electrical Engineering at The University of Massachusetts Lowell. Joshua has a keen interest in leveraging advanced Radio Frequency technologies for real world application, in this case for healthcare/bio-sensor application. Joshua has a strong background in electromagnetics, RF design, and Radar engineering. This research project on the development of a patch antenna system for glucose monitoring is a part of Joshua's Master's course work.

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Conflicts of Interest-

The author declares no conflicts of interest regarding the publication of this paper.

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