Indonesian Journal of Electrical Engineering and Computer Science
Vol. 34, No. 3, June 2024, pp. 1489~1498
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v34.i3.pp1489-1498

Optical sensor to improve the accuracy of non-invasive blood sugar monitoring

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Article Info

Article history:

Received Oct 28, 2023
Revised Feb 19, 2024
Accepted Mar 10, 2024

Keywords:

Diabetes
Glucose level
NIR spectroscopy
Non-invasive
Sensor

ABSTRACT

Optical sensors offer a painless method of monitoring blood glucose levels using various light technologies to analyze blood characteristics without penetrating the skin. The literature review part reflects the progress in optical sensor technology evaluates its potential in blood glucose monitoring by overcoming the limitations of conventional methods and recognizes the challenges and future prospects in this rapidly developing area of research. The results of empirical studies are then presented. The methodology is presented as a non-invasive method of blood glucose monitoring based on near-infrared spectroscopy. To precisely evaluate blood glucose concentrations, spectroscopy techniques involving absorption and reflection are employed at wavelengths 450, 900, 1350, and 1800 nm. After absorption and reflection of glucose molecules, light is generated. An experimental study of different samples revealed a linear relationship between the final output voltage and sugar concentration. The results demonstrate a correlation between blood glucose level and signal intensity after transmission.

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1. INTRODUCTION

Diabetes is a chronic metabolic disorder that is affecting millions of people worldwide, posing a significant global health problem. The prevalence of this condition is on the rise, partly due to changing lifestyles and an increase in obesity. If left untreated, diabetes can lead to severe complications such as cardiovascular disease, renal failure, and neuropathy. This can significantly impact the quality of life, and increase the risk of mortality [1], [2]. That is why effective diabetes management is crucial, primarily through consistent and accurate monitoring of blood glucose levels. According to the international diabetes federation (IDF), there are approximately 537 million people worldwide with diabetes, with most of them living in low- and middle-income countries. Unfortunately, every year, 1.5 million people die from diabetes [3].

Historically, blood glucose monitoring has heavily relied on invasive techniques, primarily through finger prick tests, which involve piercing the skin to extract a small blood sample. While this method is effective in providing accurate readings, it does come with several limitations [4]. Patients may find it uncomfortable and painful, leading to reduced compliance, particularly for those who require frequent monitoring [5], [6]. Furthermore, the repeated nature of this process can cause physical harm to the skin over time. Additionally, needing to perform these tests multiple times daily can create a psychological burden and may not support discreet monitoring, ultimately affecting the individual's daily routine [7]-[10].

There are various ways to analyze glucose levels, such as through the fingernail by frequency action on the nail bed [11], contact lens sensors [12]-[15] using electromagnetic sensing methods [16], and other biological fluids (sweat, urine, intercellular fluid, respiration, and saliva) [17], [18]. Some methods can be based on modelling without experimental data [19], but the advantage lies in the conceptual models anchored by results of analyses carried out under real conditions [20].

To address these issues, there is growing interest in developing noninvasive methods for monitoring blood glucose levels. Optical sensor technology has shown considerable promise among these methods [21]. Optical sensors use a variety of light-based techniques, such as near-infrared spectroscopy, Raman spectroscopy, and photoacoustic spectroscopy, to analyze blood and tissue properties without penetrating the skin. These techniques provide a painless alternative to conventional methods [22], [23], and have the potential to revolutionize diabetes management by continuously monitoring blood glucose levels in real-time without the disadvantages of invasive methods [24].

The progress of optical sensor technology marks not only a technological leap forward, but a paradigm shift in diabetes treatment [25]. Non-invasive methods can now measure blood sugar, body temperature, and heart rate [26]. This patient-friendly approach to glucose monitoring meets the urgent need for better disease management, improved treatment adherence, and ultimately, a higher quality of life for diabetics [27]. While non-invasive glucose monitoring has some margin of error, validation through comparative analysis with invasive methods is crucial [28], [29]. Once reliable results are obtained, optimization can be achieved through artificial intelligence algorithms [30], [31], mathematical and statistical models [32]-[34]. The initial stage involves approximating physical measurements [35]. Continuous glucose monitoring for enhanced patient convenience can be achieved through mobile devices, which transfer data to cloud storage via IoT devices [36], [37].

2. RESEARCH METHOD

2.1. Non-invasive technology for determining blood sugar levels

One non-invasive method for measuring glucose levels is spectroscopy. By passing a beam of light through a clear glucose solution in water, the glucose causes the light intensity to attenuate at different frequencies, creating a characteristic absorption spectrum that allows for highly accurate glucose content determination. Researchers have attempted to measure sugar content by studying the spectroscopic properties of the skin, but light can only penetrate deeply in a narrow frequency range-the infrared range [38], [39] and glucose has no specific signal in this range. Furthermore, light scattering, temperature-dependent light absorption, and light absorption structure by different skin distributions pose additional challenges [40].

In this study, we examine a non-invasive optical method for blood sugar determination that evaluates the radiation blocking the earlobe [41]. Infrared sensors are used to measure sugar levels in blood vessels, and they generate an analog voltage signal corresponding to the intensity of received light. An infrared sensor consists of a sensor and a photoreceptor, and it converts the received sequence of IR pulses into an analog output voltage. This voltage signal is then used as input for the Arduino Nano platform [42], [43].

The non-invasive blood sugar sensing system's architecture is illustrated in Figure 1, which employs the Atmel ATmega328p microcontroller as the main computing module along with a 3.3 V power supply port. In Figure 1, the blood sugar sensor's design for diabetic patients is depicted, comprising several circuit blocks labeled A-H. Figure 1(a) depicts a non-invasive measurement example, where the earlobe is positioned between an LED light emitter and an infrared sensor. The amount of radiation absorbed in the tissues and the wavelength determines the signal sent to Figure 1(b) [44], [45]. Figure 1(c) shows a non-invasive device that incorporates an LED and an infrared sensor. The Atmel ATmega328p microcontroller Figure 1(e) converts the analog signal Figure 1(d) into a digital signal 1(f). Then, the signal is filtered in Figure 1(g), which generally controls the system, including data collection, information processing, and component control. Finally, the microcontroller data is analyzed on a personal computer, Figure 1(h).

By creating the mathematical model in Figure 2 and performing calculations using the software, a direct correlation was experimentally established between the percentage of light transmitted through the organic material and the wavelength of the emitted LED. At a wavelength of 940 nm, we recorded the optical radiation passing through the organic material. We relied on Max Planck's (1), which explains the spectral energy distribution of electromagnetic radiation in thermal equilibrium with matter at a specific temperature. This formula connects the energy and frequency of radiation [46].

$$E = h \times f, \tag{1}$$

Where, h – Planck constant, f – LED emission frequency.

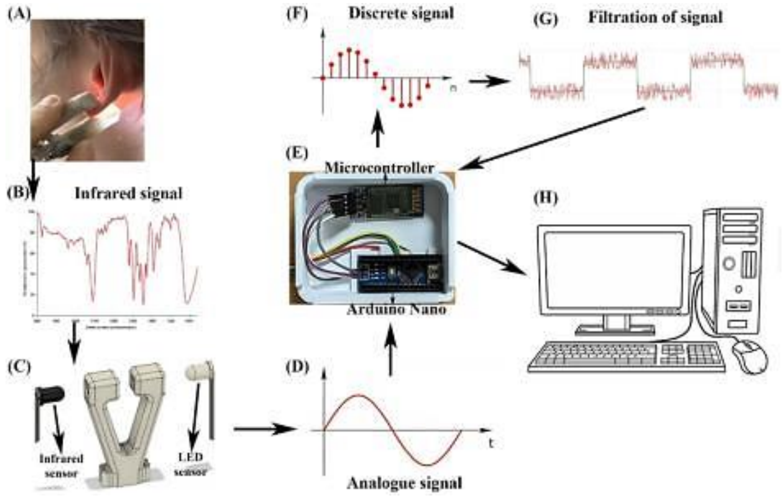

Figure 1. Architecture of a non-invasive blood sugar sensing system; (a) blood sugar sensor, (b) dependence of radiation on wavelength, (c) LED and infrared sensor, (d) analog signal, (e) microcontroller, (f) digital signal, (g) filtration of signal, (h) personal computer

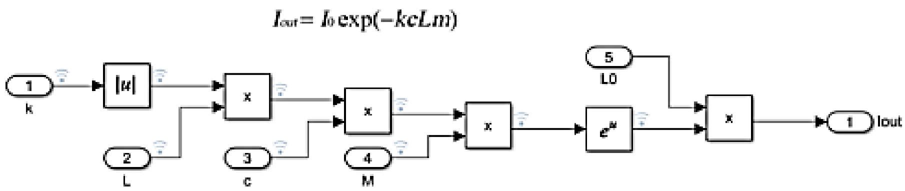

Figure 2. Mathematical model of data calculation

Utilizing a device that generates optical light and measures a quantitative variable passing through the human skin, we can determine the intensity of optical radiation after it has passed through. As light travels through human tissue, it undergoes various phenomena such as refraction, absorption, reflection, and scattering from an infrared sensor. These phenomena result in incompatible reflection and refraction of light within and outside of cells and fluids. Its concentration and the length of the path through it, according to the Pierre-Lambert law, determine the amount of light absorbed by a substance. While the detection value should remain constant in theory, fluctuations in glucose molecule concentration may cause slight variations.

$$I_{out} = I_0 \times exp\ (-k \times c \times L \times m), \tag{2}$$

Where:
I_{out} – the intensity of an LED that generates a white visible spectrum light wave with a nominal voltage of 3.4V;
I_0 – the intensity that occurs when light from an LED passes through human skin;
L – thickness of the measured layer of biological medium (in our case it is human skin);
k – absorption coefficient;
c – spectral range factor;
m – Surface state coefficient of a biological object, applied specifically to filter out interference and create a median value throughout the measurement time [47].

After processing and calibration, the output signal, represented as the percentage of glucose in the blood, changes as a result of the voltage change resulting from the change in light density after absorption. The structural diagram of the infrared sensor device is shown in Figure 3. There are 4 parts installed in the main board:
- Microcontroller;
- Power and protection chip;
- USB port for information transfer;
- Bluetooth module for data transfer.

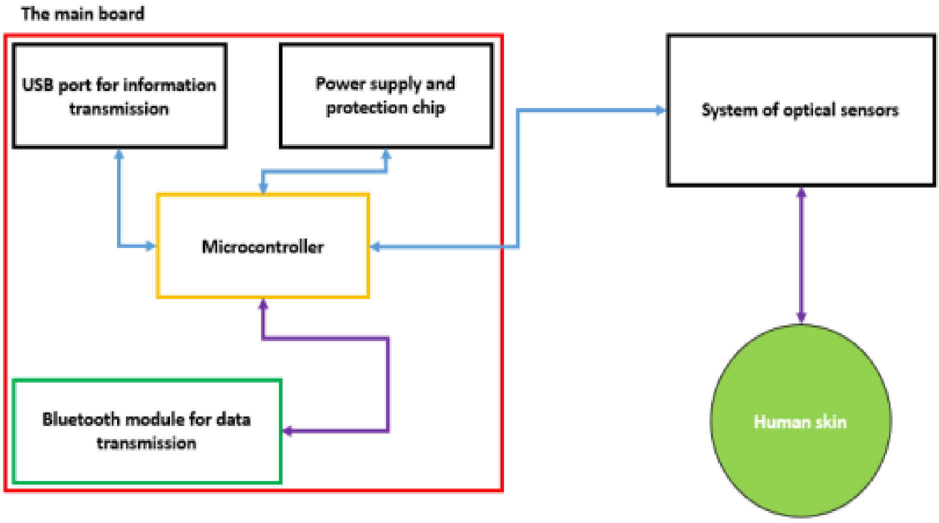

Figure 3. Structural diagram of an infrared sensor

The device operates as follows: a microcontroller is connected to an optical sensor system (ODS). When the ODS comes into contact with human skin, it reads the data and sends it to the microcontroller. The microcontroller then converts the data into information, which can be transmitted via a USB port or Bluetooth module for further analysis.

To measure blood glucose levels, the spectrometric method is used. This involves a photoelectric transducer and a light source. The transducer receives a signal from the reflected light, but this signal is weakened when the earlobe is near the light source because the light passes through the body's blood vessels and is partially absorbed. Experiments are conducted in an enclosed environment to avoid contamination from external light sources.

When the reflected light hits the photodetector, it conducts current. Using the voltage on the detector, the Arduino Nano calculates the blood glucose concentration based on a mathematical relationship obtained from non-invasive data analysis. The result is displayed on a liquid crystal display. See Figure 4 for a schematic of the near-infrared calibration (NIR)-based glucose sensor.

A power source of 9 volts DC was utilized for the supply of energy. In addition, an LM7805 voltage regulator was used to provide a constant 5 V supply to both the LED and the Arduino Nano board. Due to the series resistor in the LED circuit, this provides a constant current to the LED giving a light of constant intensity. Experiments have shown that the Arduino Nano combined with a conventional 5mm photodiode provides accurate enough measurements to make a reliable conclusion, as shown in Figure 5.

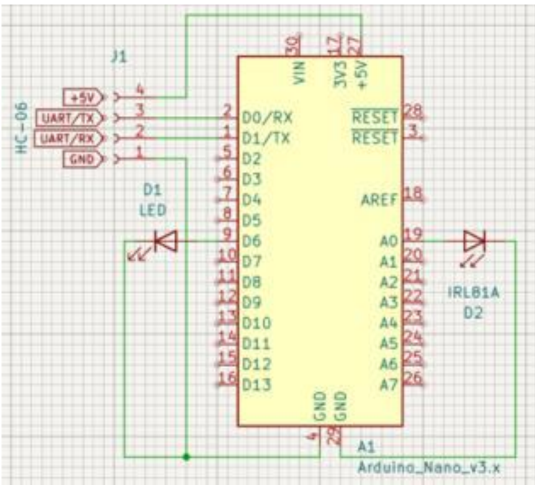

Figure 4. Electrical circuit diagram of the NIR blood glucose detector

Figure 5. Non-invasive glucose measurement device

Two main obstacles in measuring blood flow in tissue are accurately determining the amount of blood present and protecting the sensitive wiring from interference. By utilizing a gallium-indium arsenide photodiode with a wavelength range capable of working with four different LEDs (450, 900, 1,350, and 1,800 nm), these issues can be addressed [48]. Additionally, soldering the components together can help minimize any signal noise. In contrast to microprocessors, microcontrollers assume that the program loaded onto them will always be executed. This differs from digital devices with microprocessors, where the user can choose what operating system, system software, and application software to install.

3. RESULTS AND DISCUSSION

The optical range of four glucose absorption spectra -450, 900, 1350, and 1800 nm -were tested, with the most suitable absorption maximum for glucose being 940 nm. This specific wavelength is free from interference caused by human skin absorption, water absorption in skin layers, or other components present in its composition. Special LEDs and photodetectors are available for this purpose.

To measure and present these results, an appropriate instrument was used to create a graphical representation of wave distribution data along the sensor's length at intervals of 450, 900, 1,350, and 1,800 nm. The sensitivity of the device is greatly impacted by the selected wavelength regions. NIR spectroscopy is implemented through separate channels, each of which operates at a specific wavelength. These wavelengths are critical for experiments involving infrared and ultraviolet optics [49], [50]. Figure 6 shows optical data transmission models using sensors and LEDs on individual channels with specific wavelengths. Figure 7 shows the emission power depending on the luminescence temperature of the LED, where the graphical representation of the dependence of the power consumption of LEDs of different luminescence on the luminescence temperature. The best optical power is produced by the red LED from the moment of its inclusion in the electrical circuit. The use of the red LED makes it possible to create the most accurate optical data measurement systems, taking into account the required power and luminance characteristics of the LED. Graphical representation of the dependence of power factor and brightness difference. Figure 8 shows the power consumption of electric current depending on the LED luminescence.

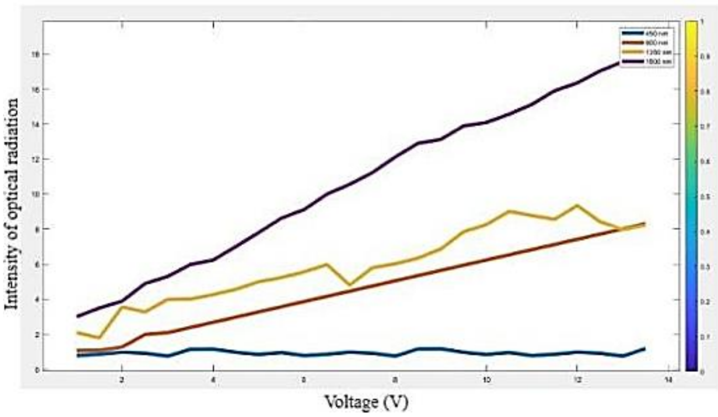

Figure 6. Graphs plotted with sensors at 450, 900, 1,350, and 1,800 nm

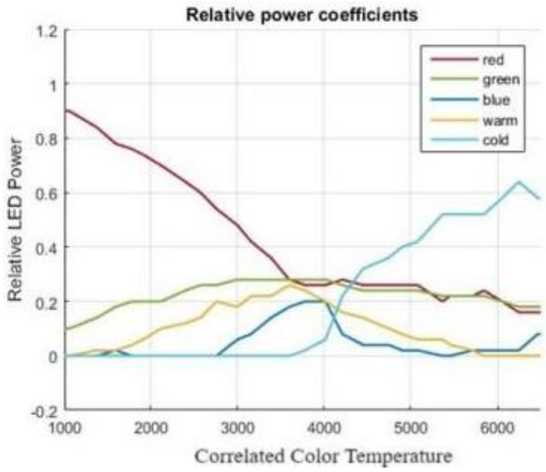

Figure 7. Radiation power as a function of LED luminescence temperature

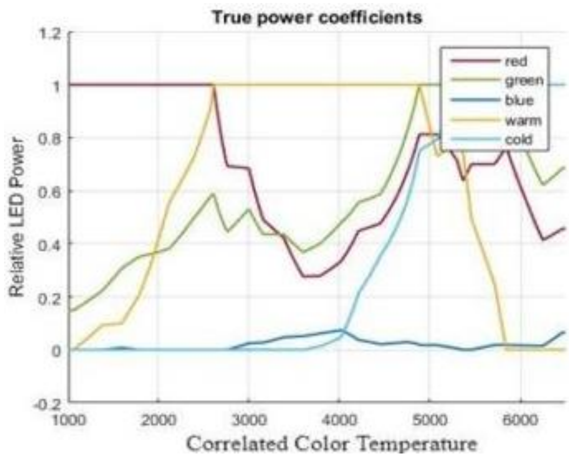

Figure 8. Electric current consumption power depending on LED luminescence

According to research [51], red LEDs are the most effective when it comes to luminescence due to their unique spectral properties. When incorporated into an electrical circuit, the red LED initiates fast and accurate illumination of the skin area, thanks to the power and speed of the red-light beam. Interestingly, the brightness of a red LED is inversely proportional to its Kelvin value-the lower the K, the redder the glow, and vice versa. It's worth noting that both infrared and red LEDs have lower power consumption during the measurement process, with red LEDs being more stable and allowing for more precise readings. This results in a linear relationship between the intensity of transmitted infrared light and sugar concentration. A graphical representation of the dependence of the LED brightness on its temperature is shown in Figure 9.

LEDs that emit infrared and red light produce lower levels of brightness when passing through human skin or other biological materials due to signal propagation in space and the effects of signal distortion. A graphical representation of sensor wavelength dependence on the amount of received light shows optical distortion after increasing the sensor wavelength beyond 1,000 nm. Sensors that detect infrared and red light can capture the LED wave more accurately and quickly compared to other sensors [52], [53]. Our team conducted tests on our sensor and observed a decrease in voltage levels as glucose concentration increased, as depicted in Figure 10.

According to research [54], [55], there is a direct correlation between the intensity of transmitted infrared light and sugar concentration. Spectrophotometry shows great potential in studying the optical properties, structure, composition, and local inhomogeneities of biotissues. This method provides a precise measurement of the extent and volume of damage to biological tissues. The major benefit of spectrophotometry is that it can register changes in epithelium and internal organ neoplasms, enabling early disease diagnosis and increasing the likelihood of successful treatment. NIR spectrophotometry has been particularly successful, as the transparency of IR light has allowed for the creation of spectral systems for visualizing tissue sections.

However, it is important to consider certain limitations of this method. The accuracy of non-invasive measurements may be affected by factors such as tissue composition, skin temperature, and hydration levels, requiring additional calibration and device adjustment. Additionally, the high cost of developing and manufacturing such devices may limit their widespread availability.

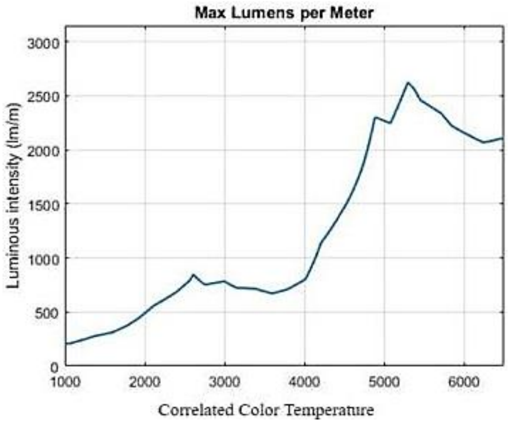

Figure 9. Dependences of LED brightness on its temperature

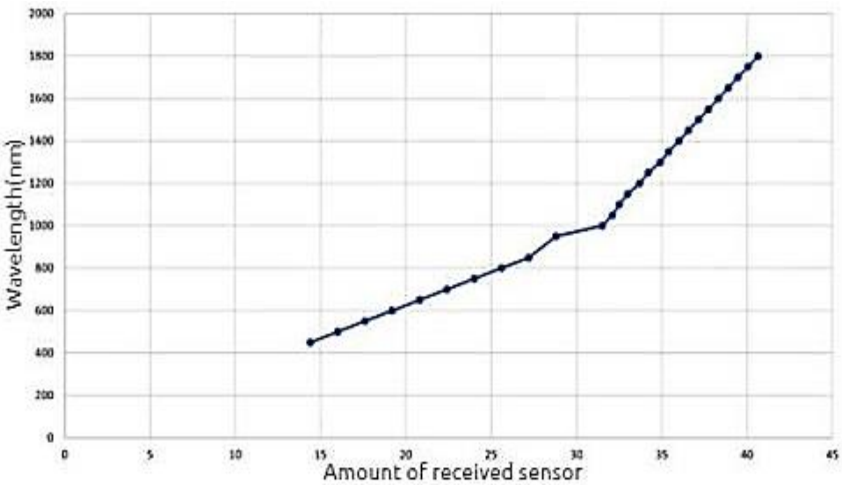

Figure 10. Dependence of the wavelength of infrared light on the amount of received sensor

4. CONCLUSION

The infrared photodiode is a highly efficient optical sensor that boasts several advantages over similar sensors. Notably, it can operate in low light conditions, making it particularly useful in dark environments or during nighttime. Unlike other optical sensors that require ample lighting to function, the infrared photodiode can detect objects even in minimal light.

An experimental study of various samples found that the relationship between sugar concentration and final output voltage is nearly linear. The results demonstrate the correlation between blood glucose levels and intensity levels following signal transmission. Overall, the infrared photodiode is a crucial component in many technological applications due to its sensitivity, speed, ability to operate in low light, and compact, lightweight design.

Moving forward, research on non-invasive blood glucose monitoring using NIR spectroscopy will involve real-world clinical trials of IoT systems. Additionally, it will be essential to continue refining data analysis algorithms to provide more accurate and rapid diagnoses. Integration with other medical technologies and systems will ultimately result in a cohesive ecosystem solution for diabetes management.

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