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Research Article

Advancements in Non-Invasive Blood Glucose Monitoring Technologies, Pioneers, and Market Trends

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Abstract

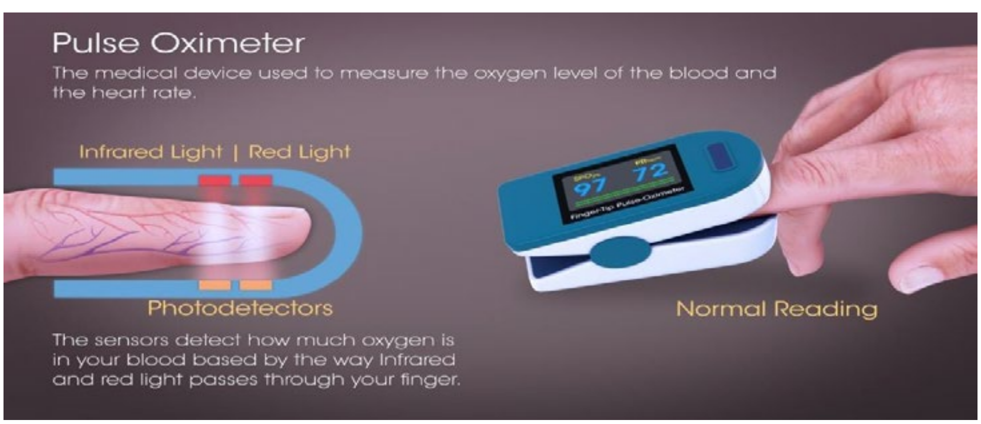
Non-invasive blood glucose monitoring has been a long-sought goal for diabetes management, aiming to eliminate the need for painful finger-prick tests. Recent advancements in optical and biosensor technologies have enabled the development of wearable glucose monitors that provide continuous, real-time measurements. This article explores the physics and mathematical principles underlying pulse oximetry-based glucose monitoring, recent market developments, and key players in this emerging field. It also discusses the role of Artificial Intelligence (AI) in enhancing accuracy, the regulatory landscape, and future directions for non-invasive glucose monitoring technologies.

Keywords: Glucose, Monitoring, Non-invasive, AI (Artificial Intelligence), Wearable, Photoplethysmography (PPG), Optical, Diabetes, Spectroscopy, Signal Processing

1. Introduction

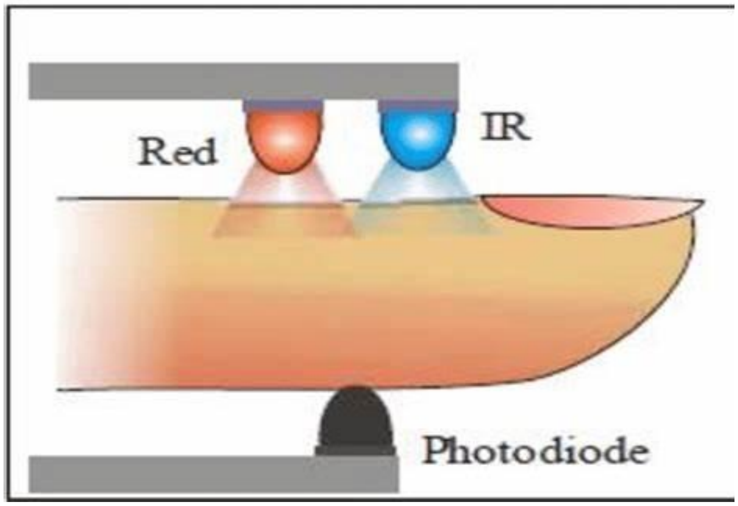
Diabetes management relies heavily on frequent blood glucose monitoring to prevent complications. Traditionally, this has been achieved through invasive finger-prick tests and Continuous Glucose Monitors (CGMs) that require subcutaneous sensor implantation. However, the demand for non-invasive glucose monitoring has driven research into optical, electrochemical, and biosensing technologies.

Pulse oximetry, a well-established method for measuring blood oxygen saturation, is now being explored for non-invasive glucose monitoring. By leveraging the optical properties of glucose and its interactions with light in the Near-Infrared (NIR) and Mid-Infrared (MIR) spectrum, researchers aim to develop reliable, non-invasive devices as illustrated in Figure 1 and Figure 2. This article delves into the underlying physics, mathematical models, market availability, pioneers leading this revolution, and how AI plays a crucial role in refining technology.



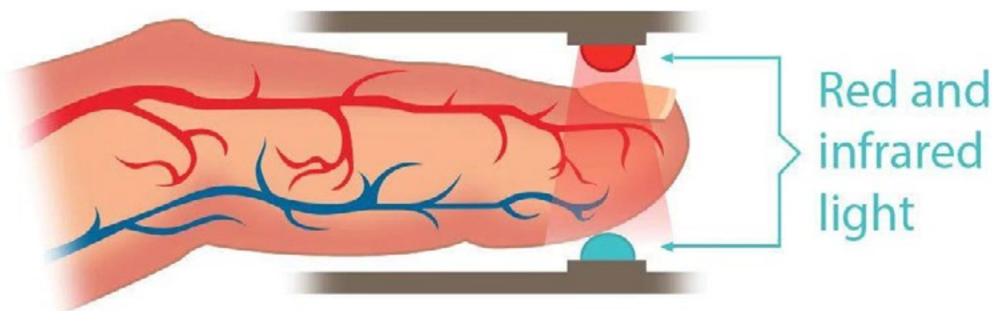
Source: www.amazon.com

Figure 1: Pulse Oximeter Cross-Section Image



Source: www.wikipedia.org

Figure 2: Basic Idea of a Pulse Oximeter of Hemoglobin Principle at Red and Infrared



Source: www.wikipedia.org

Figure 3: Pulse Oximeter Schematic Diagram

Overall, pulse oximetry is a noninvasive optical technique widely used for monitoring blood oxygen saturation (SpO_2) and heart rate. However, researchers have been exploring its application for non-invasive blood glucose measurement, which could revolutionize diabetes management by eliminating the need for frequent finger pricks.

All in all, Pulse oximetry-based blood glucose measurement holds great potential as a noninvasive technique, but further advancements in infrared spectroscopy, AI-driven signal processing, and personalized calibration are needed to achieve clinical-grade accuracy. As technology evolves, noninvasive glucose monitoring may become a practical reality for diabetes management.

2. Working Principle of Pulse Oximetry

Traditional pulse oximetry relies on the differential absorption of light at two wavelengths (typically 660 nm - red light, and 940 nm - infrared light) through pulsatile blood flow in the capillaries. The ratio of absorbed light is used to estimate oxygen saturation. See Figure 2 and Figure-3 as well.

As of February 2025, non-invasive blood glucose monitoring devices are emerging in the market, aiming to provide alternatives to traditional finger-prick methods. These devices utilize various technologies, including optical methods like pulse oximetry, to estimate blood glucose levels without penetrating the skin.

The landscape of non-invasive blood glucose monitoring is evolving, with several companies pioneering technologies to provide alternatives to traditional methods. While some devices are available over-the-counter, it is crucial to stay informed about their regulatory status and consult healthcare providers to ensure their suitability for individual health needs.

In respect to regulatory consideration, as we stated it is important to note that while these devices are becoming more accessible, the U.S. Food and Drug Administration (FDA) has not authorized, cleared, or approved any smartwatch or smart ring intended to measure or estimate blood glucose levels on its own. Users should exercise caution and consult healthcare professionals when considering the use of such devices as depicted in Figures 1 through -3 for medical purposes yet.

Recent Developments in Non-Invasive Glucose Monitoring Devices are listed below as beginning of 2025 and they are

• reuters.com
Abbott follows rival Dexcom with OTC glucose monitor launch in US.
160 days ago

Note that DexCom's Stelo is an Over-The-Counter (OTC) Continuous Glucose Monitor (CGM) that provides real-time blood glucose readings via a smartphone app, expanding accessibility beyond traditional prescription-based CGMs.

CGMs (Continuous Glucose Monitors) are wearable medical devices that continuously track blood glucose levels in real-time. They use a small sensor inserted under the skin to measure glucose in interstitial fluid and transmit data to a receiver, smartphone, or smartwatch. CGMs help individuals with diabetes manage their condition by providing insights into glucose trends, detecting fluctuations, and reducing the need for frequent finger-prick tests. Advanced models integrate AI and predictive analytics to enhance accuracy and personalized diabetes management.

• barrons.com
Sugar High: How a Glucose Monitor Told Me Startling Things About My Diet.
143 days ago

• wired.com
Review: Abbott Lingo Continuous Blood Glucose Monitor
21 days ago.

While the pioneers in Non-Invasive Glucose Monitoring are:

Afon Technology: Afon Technology is developing **Glucowear™**, a completely non-invasive, continuous blood glucose monitor. This device aims to empower individuals with diabetes by providing real-time glucose data without the need for invasive procedures.
afontechnology.com

Know Labs: Know Labs is working on the **KnowU**, a non-invasive, wearable continuous blood glucose monitor. Their technology focuses on identifying and measuring molecules in the body without the need for invasive sampling.
https://www.knowlabs.co/?utm_source=chatgpt.com

However, the current market offering are given by the following medical device companies are

Abbott's Lingo: Abbott has introduced the **Lingo** continuous glucose monitoring system in the U.S. market. Designed for adults not on insulin therapy, Lingo consists of a coin-sized adhesive skin patch that transmits blood sugar readings to a smartphone via Bluetooth. Pricing starts at $49 for a two-week sensor.
reuters.com

DexCom's Stelo: DexCom has launched the **Stelo** continuous glucose monitor, also targeting non-insulin-dependent individuals. Like Lingo, Stelo provides continuous blood glucose readings through a wearable sensor that connects to a smartphone app. The device is available Over-The-Counter, expanding access beyond traditional prescription-based models.
barrons.com

3. Mathematical and Physical Analysis of Pulse Oximetry for Blood Glucose Measurement

The Mathematical and Physical Analysis of Pulse Oximetry for Blood Glucose Measurement explores how glucose concentration affects light absorption, scattering, and refractive index in blood, using principles like Beer-Lambert Law and Mie Theory to estimate glucose levels non-invasively.

This section details the mathematical foundations behind optical glucose sensing, including absorption coefficients, scattering behavior, and signal processing techniques like Photoplethysmography (PPG). AI-enhanced models refine these signals by filtering noise and improving measurement accuracy for non-invasive glucose monitoring.

3.1 Optical Absorption and Beer-Lambert Law

The fundamental principle governing pulse oximetry and glucose measurement is the Beer-Lambert Law, which describes how light is absorbed as it passes through a medium:

$$I = I_0 e^{-\mu_a d} \tag{1}$$

Where:

I = Transmitted light intensity.
I_0 = Incident light intensity from the source.
μ_0 = Absorption coefficient (dependent on glucose concentration and wavelength)
d = Optional path length through the tissue.

For *multi-wavelength absorption,* we extend the equation to account for different chromophores:

$$I(\lambda) = I_0(\lambda) e^{-\left[\varepsilon_{HbO_2}(\lambda) C_{HbO_2} + \varepsilon_{Hb}(\lambda) C_{Hb} + \varepsilon_G(\lambda)\right] d} \tag{2}$$

Where:
• $\varepsilon_{HbO_2}(\lambda)$, $\varepsilon_{Hb}(\lambda)$, $\varepsilon_G(\lambda)$ are molar absorption coefficients of oxyhemoglobin, deoxyhemoglobin, and glucose, respectively, at wavelength λ.
• C_{HbO_2}, C_{Hb}, C_G are the concentrations of oxyhemoglobin, deoxyhemoglobin, and glucose.

Since glucose absorbs weakly in the visible range, Near-Infrared (NIR) wavelengths (900–2500 nm) are used, where glucose absorption is more prominent.

3.2 Optical Scattering and the Mie Theory

In biological tissues, light does not only get absorbed but also scatters due to interactions with red blood cells, proteins, and glucose molecules. This scattering is described by Mie scattering theory, where the scattering coefficient μ_s is given by:

$$\mu_s = N\sigma_s \qquad (3)$$

Where:

• N = Number density of scatterers (blood cells, glucoses molecules).
• σ_s = Scattering cross-section.

The *total attenuation coefficient* μ_t (which includes both absorption and scattering) is given by:

$$\mu_t = \mu_a + \mu_s \qquad (4)$$

Glucose changes the refractive index of interstitial fluid, affecting scattering properties. The relationship between glucose concentration C_G and refractive index follows:

$$n = n_0 + kC_G \qquad (5)$$

where k is a proportionally constant. As n changes, light scattering angles and intensity also change, which can be detected in a pulse oximeter.

3.3 Photoplethysmography (PPG) Signal Processing

Pulse oximeters measure *pulsatile blood volume changes using Photoplethysmography* (PPG). The PPG signal consists of an *AC component (due to arterial pulsation)* and a *DC component (due to non-pulsatile tissue absorption).* The AC-to-DC ratio at different wavelengths is used to estimate glucose concentration.

For a given wavelength λ, the PPG signal is:

$$(PPG(\lambda,t) = AC(\lambda,t) + DC(\lambda,t) \qquad (6)$$

The AC/DC ratio, which depends on glucoses concentration, is given by:

$$R_{AC/DC} = \frac{AC(\lambda_1)/DC(\lambda_1)}{AC(\lambda_2)/DC(\lambda_2)} \qquad (7)$$

where λ_1 and λ_2 are selected wavelengths in the Near-Infrared (NIR) range.

3.4 Machine Learning & Signal Calibration

To extract glucose concentration, machine learning techniques such as Principal Component Analysis (PCA), Partial Least Squares Regression (PLSR), and Neural Networks are used to analyze the spectral signals and separate glucose-dependent absorption from other noise sources.

A general regression model for glucose prediction is:

$$C_G = f(PPG_{\lambda_1}, PPG_{\lambda_2}, \cdots, PPG_{\lambda_n}, \mu_a, \mu_s, R_{AC/DC}) \qquad (8)$$

where f is a nonlinear mapping function trained on calibration data.

3.5 Signal-to-Noise Ratio (SNR) Analysis

Since glucose signals are weak, the Signal-to-Noise Ratio (SNR) is crucial. The SNR is defined as:

$$SNR = \frac{\text{Power of glucose-related signal}}{\text{Power of noise (motion artifacts, ambient light, etc.)}} \qquad (9)$$

To improve SNR the following points can be taken into consideration:

• **Filtering techniques** like adaptive filtering and wavelet denoising are used.
• **Multi-sensor fusion** (combining optical, thermal, and electrical sensors) enhances accuracy.
• **AI-based noise reduction** using deep learning models refines glucose estimation.

In conclusion, we state that by integrating optical absorption (Beer-Lambert Law), scattering (Mie Theory), PPG signal processing, and AI-driven spectral analysis, pulse oximetry can potentially be used for noninvasive glucose monitoring. However, challenges like low signal strength, inter-individual variability, and motion artifacts require further research and technological advancements for clinical implementation.

3.6 AI's Role in Non-Invasive Glucose Monitoring

AI plays a crucial role in non-invasive glucose monitoring by enhancing signal processing, predictive analytics, and wearable device integration, improving accuracy and personalizing glucose estimation for users [1-3].

By leveraging machine learning (ML), deep learning, and real-time data analysis, AI helps filter noise from optical signals, calibrate devices for individual users, and integrate glucose monitoring with smartwatches, IoT devices, and mobile health apps, making diabetes management more efficient and accessible.

For the purpose Artificial Intelligence (AI) application driven pulse oximetry the following points can be considered as:

3.7 AI Driven Signal Processing and Noise Reduction

Ai enhances glucose monitoring by applying Machine Learning (ML) models to raw Photoplethysmographic (PPG) and Near-Infrared Spectroscopy (NIRS) signals. These models filter out noise from movement, ambient light fluctuations, and physiological variations.

3.7.1 Predictive Analytics for Personalized Calibration

Traditional non-invasive glucose monitors suffer from variability across individuals. AI-driven predictive modeling helps calibrate devices to a user's specific physiological characteristics, reducing errors and improving accuracy.

3.7.2 Integration with Wearable and IoT Devices

AI enables seamless integration of non-invasive glucose monitoring with smartwatches, fitness trackers, and mobile health apps. Real-time AI analytics can alert users to significant glucose fluctuations and suggest lifestyle interventions.

3.7.3 Deep Learning for Improved Spectral Analysis

Deep learning algorithms, such as Convolutional Neural Networks (CNNs) as part of Deep Learning functionality and Recurrent Neural Networks (RNNs) as well, to enhance spectral analysis by detecting subtle changes in glucose-induced optical absorption and scattering patterns.

3.7.4 Challenges in Pulse Oximetry-Based Glucose Monitoring

Challenges in pulse oximetry-based glucose monitoring include low signal-to-noise ratio, variability in skin properties, motion artifacts, and the need for individualized calibration, making accurate non-invasive glucose measurement complex.

At a very holistic approach to the topic of challenges in pulse oximetry-based glucose monitoring, the following bolt-points can be explored as:

Low Signal-to-Noise Ratio

• Blood glucose concentration has a weak influence on light absorption compared to oxygenated and deoxygenated hemoglobin, making it challenging to isolate glucose-specific signals.

Variability in Skin and Tissue Properties

• Skin pigmentation, hydration levels, and tissue composition can affect optical readings, leading to inter-person variability.

Environmental and Motion Artifacts

• Changes in temperature, movement, and ambient light conditions can interfere with measurements.

Calibration and Accuracy

• Unlike SpO_2 measurement, which relies on well-established calibration models, glucose monitoring requires individualized calibration to account for differences in skin and tissue properties.

4. Future Prospect and Conclusion

The future of non-invasive glucose monitoring lies in **multi-sensor integration, AI-driven signal processing, and hybrid technologies** combining optical and electrochemical methods. As research progresses, AI will play a crucial role in achieving clinical-grade accuracy, enabling real-time monitoring, and personalizing diabetes management [4-7].

Non-invasive glucose monitoring is at an exciting juncture, with companies like **Abbott, DexCom, Afon Technology, and Know Labs** driving innovation. AI-driven advancements in **signal analysis, predictive modeling, and wearable integration** are set to transform diabetes management, making it more accessible, convenient, and effective for millions worldwide.

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