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Analysis of Non-Invasive Diabetes Detection Technology

Ayimureke Asikar *

School of Chemical and Environmental Engineering, Shanghai Institute of Technology, Shanghai, China

* Corresponding Author Email: kimaymurok@gmail.com

Abstract. Diabetes mellitus is a chronic disease caused by a combination of genetic, environmental, and lifestyle factors, posing a serious threat to public health worldwide. Traditional blood glucose monitoring methods have the disadvantages of high invasiveness, complicated operation, and poor portability, which affect the testing experience of patients and the effectiveness of disease management. Therefore, the search for new non-invasive, convenient and accurate diabetes detection methods has become a research hotspot. This research describes some of the current state-of-the-art diabetes detection technologies, with a focus on optical technologies, electrochemical sensors, continuous glucose monitoring (CGM) systems, and telemedicine solutions incorporating artificial intelligence and the Internet of Things (IoT). These new technologies enable non-invasive blood glucose monitoring by analyzing glucose concentrations in body fluids, improving patient experience and disease management. In addition, genetic and metabolic research, portable testing devices, and novel therapeutic approaches offer new possibilities for early diagnosis and personalized treatment of diabetes. By taking a deeper look at these new technologies, this research provides new ideas and directions for the future management of diabetes.

Keywords: diabetes; non-invasive detection; optical sensing; biosensing; continuous monitoring technology.

1. Introduction

Diabetes mellitus is a chronic disease with complex causes, but mainly involves genetic, environmental and lifestyle factors. Some people may be more susceptible to diabetes because of genetic factors, while others may be affected by lifestyle factors such as unhealthy diet, physical inactivity, obesity, high blood pressure and high cholesterol. On 6 December 2021, the official website of the International Diabetes Federation (IDF) released the Global Diabetes Map 2021, which shows that there are 537 million cases of adult diabetes globally in 2021, affecting about 1 in 10 adults worldwide. The prevalence of diabetes is projected to rise further to 12.2 per cent by 2025, with the number of cases increasing to 783 million. The number of people with diabetes globally is showing a continuous increase, mainly due to factors such as an ageing population, unhealthy lifestyles and increasing rates of obesity. In diabetes mellitus, high blood glucose concentration leads to metabolic disorders and a series of complications, which seriously reduces the quality of life of patients, and the development of the disease can lead to disability or even death. Diabetes not only has a serious impact on the patient's quality of life, but may also lead to many serious complications, such as cardiovascular disease, nephropathy and retinopathy, causing a huge burden on the healthcare system and socioeconomics. Patients with diabetes need regular testing of blood glucose levels, long-term treatment and control with relevant medications, and long-term monitoring and care for the various complications caused by diabetes.

Diabetes requires regular monitoring of blood glucose levels to ensure effective treatment and management. Although conventional diabetes detectors play a key role in blood glucose monitoring, they have some drawbacks that limit their use in diabetes management. Conventional diabetes detectors are highly invasive. These detectors usually require blood sampling, where blood is drawn through a puncture in the skin for blood glucose measurement. This invasive procedure can lead to complications such as pain, discomfort and infection, affecting the patient's testing experience and quality of life. Conventional diabetes detectors do not provide continuous glucose monitoring.

Patients are required to perform glucose tests at specific points in time and are unable to obtain continuous glucose monitoring data, which may result in missing glucose fluctuations at critical moments, affecting treatment efficacy and disease management. Conventional diabetes detectors are more complex to operate, and the use of these devices requires certain operating skills and training. Patients need to learn how to properly use devices such as blood glucose instruments and test strips, which increases the cost of learning and the difficulty of operation for patients. Conventional diabetes testing is highly affected by environmental factors. For example, factors such as temperature and humidity may affect the accuracy of the test results, and patients need to pay attention to the environmental factors during testing to ensure the accuracy and reliability of the test results. Conventional diabetes testers are not portable enough. These devices are usually bulky and heavy, requiring the carrying of blood glucose instruments, test strips and other equipment, which is inconvenient to carry around, especially for patients who need to perform blood glucose monitoring frequently, adding to the burden and inconvenience of daily life. To improve patients' testing experience and treatment effect, seeking new, more accurate, convenient and comfortable diabetes testing methods has become one of the hotspots of current research.

Currently, research on diabetes detection technologies covers a wide range of fields from basic science to clinical applications, and continues to drive innovation and progress in diagnosis and management methods. Non-invasive monitoring technologies are an important direction [1], including the development of optical technologies and electrochemical sensors, which enable non-invasive glucose monitoring by analyzing glucose concentrations in skin, sweat, tears or saliva. Continuous glucose monitoring (CGM) systems are also improving, with a focus on increasing sensor accuracy, extending service life and reducing the need for calibration to enhance the patient experience. Meanwhile, artificial intelligence and big data analytics are increasingly being used in diabetes management. Through machine learning algorithms, blood glucose data analysis and prediction have become more accurate, and personalized management recommendations have become more effective. In addition, telemedicine with Internet of Things (IoT) technology enables real-time monitoring of patients' blood glucose data and immediate guidance from doctors. Biomarker research has also provided new ideas for the early diagnosis of diabetes, and the discovery and application of new biomarkers can help improve the accuracy of diagnosis. The development of portable testing devices should not be overlooked. Portable blood glucose meters and testing functions integrated in smartphones provide patients with more convenient means of monitoring blood glucose. Genetic and metabolic research has further revealed the pathological mechanisms of diabetes. Genetic testing and metabolomic analysis not only help to assess the risk of diabetes, but also provide a scientific basis for personalized treatment. Novel therapeutic methods, such as stem cell therapy and immunotherapy, represent an important direction for the future treatment of diabetes, and are expected to fundamentally change the treatment strategy of diabetes by regenerating pancreatic islet cells or regulating the immune system. Multi-directional research on diabetes detection technologies offers a broad prospect for early diagnosis, personalized treatment and effective management, and promotes the continuous development of diabetes prevention and treatment.

This research will introduce some of the latest diabetes detection methods and discuss their principles, advantages and application prospects. These new methods cover a wide range of areas from non-invasive monitoring technologies to smart health monitoring, providing new hope and opportunities for diabetes management. By gaining a deeper understanding of these new technologies, we can better understand the dynamics of current research and provide new ideas and directions for future diabetes management.

2. New methods for diabetes detection

2.1. Optical sensing technologies in diabetes detection

Optical sensing technologies have made breakthroughs in the field of diabetes detection, providing patients with a more convenient and non-invasive means of monitoring their blood glucose. These advanced optical devices, such as near-infrared spectroscopy, Raman spectroscopy, and optical coherence tomography (OCT) devices, are capable of assessing blood glucose levels by detecting optical signals in the skin and tissues. The core principle of these technologies is to irradiate biological tissues with specific wavelengths of light and measure the light signals absorbed, scattered or reflected. Sugar molecules have unique absorption peaks for these specific wavelengths of light, and by analyzing changes in these optical signals, blood glucose concentrations can be accurately deduced. For example, near-infrared (NIR) spectroscopy takes advantage of the skin's absorption properties of NIR light, while Raman spectroscopy reflects blood glucose levels by detecting the interaction of light with molecular vibrational modes, and OCT enables the detection of diabetes-related complications, such as retinopathy, by generating high-resolution tissue images. Clinical trials and studies have shown that optical sensing technology is highly accurate and stable in blood glucose monitoring. The non-invasive nature greatly reduces the discomfort and risk of infection that patients commonly experience with traditional blood glucose monitoring. In addition, these technologies offer the advantage of rapid and continuous monitoring, allowing patients to be aware of their blood glucose changes in a more real-time manner. As technology continues to evolve, the performance of optical sensing devices continues to improve, as does their accuracy and reliability. These advances not only enhance the application value of the devices, but also provide new possibilities for diabetes management. In the future, optical sensing technology is expected to play a more important role in the early diagnosis, daily monitoring and complication prevention of diabetes.

Golparvar et al. applied stimulated Raman scattering (SRS) technology to glucose concentration monitoring for the first time, demonstrating its great potential in non-invasive blood glucose monitoring [1]. The SRS technique significantly improves the sensitivity and selectivity of the assay by enhancing the Raman effect compared to the conventional spontaneous Raman scattering process. In the study, a linear calibration curve was recorded for concentrations up to 100 mol/m^3, with a theoretical detection limit of 3.5 mol/m^3, and a highly sensitive detection was achieved in an integration time of only 0.6 seconds. In addition, the study evaluated the required average laser power and verified the feasibility in intact human serum glucose measurements. By identifying the characteristic Raman shift peaks around 1130 cm ^{1}, a highly selective detection mechanism was established, opening up new possibilities for future wearable medical devices [1].

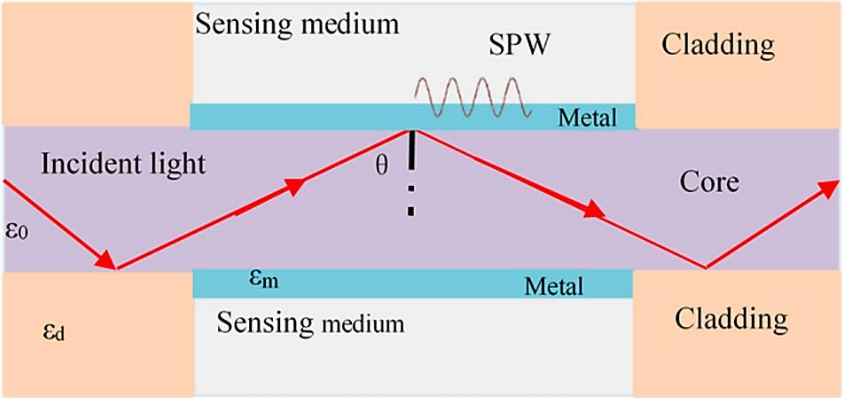

Fig. 1 Schematic illustration of optical fiber SPR sensor [2].

Zhao et al. present recent research progress in temperature self-compensation of optical fibre surface plasmon resonance (SPR) sensors [2]. Such sensors are highly promising for applications in environmental monitoring, biochemical sensing, and medical diagnostics, mainly due to their high sensitivity and the advantages of label-free detection. As shown in Fig. 1, the basic principle of temperature self-compensating fibre-optic SPR sensors is to detect the refractive index change of the environment by using the resonance of free electrons on the metal surface, whereas the temperature change affects the refractive indices of both the metal and the medium, and thus the position of the resonance peak of the SPR. And a variety of fibre optic micro/nanostructures for temperature self-compensated sensing are also presented, including multimode fibre-single mode fibre-multimode fibre (MMF-SMF-MMF) structures, U-shaped plastic fibre structures, and so on. These structures achieve the compensation of temperature changes by coating temperature-sensitive materials on the surface of the optical fibre. The research results achieved in recent years in the field of temperature self-compensating fibre optic SPR sensors are discussed in detail. For example, the use of polydimethylsiloxane (PDMS) as a temperature-sensitive material in combination with different optical fibre structures has enabled temperature-compensated sensing with high sensitivity and accuracy. Fibre optic SPR sensors combined with temperature self-compensation techniques have made significant progress in improving detection accuracy and reliability. These sensors have a wide range of applications in environmental monitoring, biomedical diagnosis and other fields [2].

By combining PPG signals with other physiological signals, more diabetes-related features can be extracted, and the accuracy and robustness of detection is improved. Multimodal data fusion helps capture more comprehensive physiological information and provides richer input data for machine learning models. Traditional machine learning algorithms such as support vector machines (SVMs) and random forests (RFs) perform well in diabetes detection, but deep learning models such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs) have significant advantages in handling complex temporal and nonlinear data. Deep learning models are able to automatically extract high-dimensional features and improve detection accuracy. With the development of wearable devices, real-time monitoring of PPG signals has become possible. With embedded machine learning algorithms, these devices are able to continuously monitor the user’s physiological state during daily life and assess diabetes risk in real time. This personalized approach to health management helps in early detection of diabetes and taking preventive measures. Due to limited data on diabetic patients, data augmentation techniques and transfer learning methods are widely used to enhance model performance. These methods can alleviate the problem of insufficient data and improve the ability of models to generalize across different populations and environments. Combining cloud computing with edge computing can improve system responsiveness and data privacy protection while ensuring data processing efficiency. Edge computing can perform preliminary data processing on local devices, while cloud computing is responsible for complex model training and large-scale data analysis. Personalized models provide more accurate diabetes detection results by learning the unique physiological characteristics of each user. Adaptive learning algorithms can continuously update the model based on the user's dynamic physiological changes, keeping the test highly accurate and real-time.

Oliveira et al. proposed a method for non-invasive diabetes detection using photoplethysmographic volumetric (PPG) signals in combination with machine learning algorithms [3]. PPG is an optical technique for obtaining cardiovascular information by measuring the change in blood volume under the skin. The study extracted 104 morphological features from the PPG signal, including pulse width, area, and inter-peak interval, and combined them with metadata. Two machine learning algorithms, Logistic Regression (LR) and Extreme Gradient Boost (XGBoost), were used for classification and prediction. A publicly available dataset was used for the study, including 453 PPG cycles from 86 subjects, of which 172 cycles were from diabetic patients. The independence of the training and test datasets was ensured by five-fold cross-validation to prevent model overfitting. The logistic regression and XGBoost models had F1 scores of 58.8% and 51.7% in diabetes detection, with AUC values of 79.2% and 73.6%, respectively. This study demonstrates that PPG signal analysis combined with machine learning algorithms has significant potential in non-invasive diabetes detection [3].

Significant progress has been made in the application of breath analysis techniques to blood glucose measurement. For example, devices such as DiabeticSense use sensors to detect volatile organic compounds (VOCs) in breath samples that correlate with blood glucose levels, providing a non-invasive way to monitor diabetes. Clinical trials have shown this method to be accurate and convenient, making it a strong alternative to traditional blood glucose monitoring. Breath analysis techniques can effectively reflect blood glucose levels in the body by detecting specific VOCs. This non-invasive technique not only reduces patient pain but also reduces the risk of infection compared to traditional blood glucose monitoring methods. As technology continues to advance, the accuracy and reliability of breath analysis equipment is also improving, providing a more convenient option for diabetic patients to monitor their blood glucose. Overall, the application of breath analysis technology in diabetes management is promising, and with continued research and clinical validation, this technology is expected to become an important tool in the daily management of diabetic patients in the future.

An Arduino-based non-invasive blood glucose measurement device was developed [4]. The device uses breath analysis technology to infer blood glucose levels by analyzing changes in the concentration of specific chemicals in the exhaled breath sample, thus avoiding the pain and inconvenience of traditional glucose meters that require blood collection. The core components of the device include an Arduino microcontroller, a sensor module and a display module. The sensor module is responsible for collecting the user’s breath sample and transmitting the data to the Arduino for processing and analysis. Through a pre-established mathematical model, the device can calculate the user’s blood glucose level based on the sensor data and display the result on the screen. The experimental results show that this Arduino-based non-invasive blood glucose measurement device has high accuracy and reliability, with an average error rate of 1.91% and a reading accuracy of about 98.09%. These data suggest that the device performs well in terms of accuracy and reliability and can provide an effective means of blood glucose monitoring for diabetic patients. Overall, the study succeeded in developing an innovative blood glucose measurement technique that provides a more convenient and comfortable alternative to the discomfort and risk of infection associated with blood collection. Although the device performed well in the experiment, the researchers also pointed out that the device may face issues such as sensor sensitivity and optimization of data processing algorithms in real-world applications, which require further research and improvement. This novel device has an important potential for application and development in the daily glucose monitoring of diabetic patients [4].

The use of aptamer sensors for the detection of diabetes biomarkers is described [5]. The working principle of aptamer sensors is based on the specific binding of aptamers to target molecules. These target molecules include glucose, insulin, glycated haemoglobin (HbA1c), glycated human serum albumin. Aptamer sensors have demonstrated significant advances in detection sensitivity, selectivity, and assay device performance. These sensors are able to differentiate between type 1 diabetes, type 2 diabetes, and mitochondrial diabetes. The aptamer sensors have the advantages of high stability, low toxicity, and ease of modification compared to conventional assays, making them an important tool for future diabetes diagnosis. As technology continues to advance, these sensors have promising applications in the early, rapid and accurate detection of diabetes. Future studies will further optimise the performance of aptamer sensors to increase their value in clinical diagnosis [5].

A highly sensitive thin-film transistor (TFT) salivary glucose sensor was developed [6]. This innovative technology is expected to replace traditional blood glucose testing methods, avoiding the discomfort of fingertip blood collection. The sensor uses a thin semiconductor layer of indium oxide and zinc oxide covered with glucose oxidase. When a saliva sample is placed on the sensor, glucose oxidase oxidizes the glucose in it to form D-gluconolactone and hydrogen peroxide. Electrons from the electrochemical oxidation of hydrogen peroxide enter the semiconductor layer and change the current flowing through the semiconductor. By measuring this change in current, the concentration of glucose in saliva can be determined. The research team tested saliva samples containing different concentrations of glucose and analyzed saliva samples from volunteers after fasting. The results showed that the device was able to accurately measure a wide range of glucose concentrations in less than a minute and was insensitive to other molecules in saliva such as fructose and sucrose. Although the sensitivity of the sensor decreased slightly over time, it still showed good performance after two weeks of storage at room temperature. The team is currently developing sensor arrays capable of detecting a wide range of salivary metabolites simultaneously and exploring the possibility of integrating these portable sensor arrays with smartphones. This will further enhance the portability and intelligence of the device and facilitate the daily monitoring of diabetic patients [6].

2.2. Application of continuous monitoring technology

In recent years, continuous monitoring technologies and smart health monitoring systems have made significant progress in diabetes detection and management. These technologies provide patients with more accurate and timely health data by monitoring blood glucose levels in real time. CGM devices are able to provide blood glucose readings every few minutes, significantly improving the effectiveness and accuracy of diabetes management. In addition, modern CGM devices are designed to be more comfortable and convenient, and seamless integration with smart devices allows users to view blood glucose data in real time and receive personalized health advice and alerts via their smartphones or other devices. These innovations not only help to optimize the management of existing diabetes patients, but also play an important role in preventing the progression of pre-diabetes to type 2 diabetes, providing patients with a more comprehensive health monitoring solution.

Gavin et al. discussed recent advances in CGM technology in diabetes management and its future prospects [7]. Modern CGM devices are capable of providing real-time blood glucose readings every few minutes, significantly improving the effectiveness and accuracy of diabetes management. For example, the Mean Absolute Relative Difference (MARD) of the Dexcom G6 device has been reduced to 9%, providing accurate blood glucose data without the need for calibration. CGM technology significantly improves glucose control in diabetic patients, reduces the risk of hypoglycaemia and helps prevent the development of type 2 diabetes. Patients using CGM can better understand and manage their blood sugar fluctuations. Real-time data monitoring not only helps to optimize the management of existing diabetic patients, but also plays an important role in the progression of prediabetes to type 2 diabetes. In the future, CGM technology is expected to integrate with other health monitoring devices and systems to provide a comprehensive health monitoring solution. By combining artificial intelligence and big data analytics, CGM technology will be able to provide more personalized diabetes management recommendations to help optimize patient outcomes [7].

A big data intelligence-based diabetes monitoring system aimed for application in smart and healthy cities was developed [8]. The system combines various machine learning algorithms such as K-nearest neighbour, decision tree, deep learning, support vector machine (SVM), random forest, AdaBoost and logistic regression for diabetes prediction and management. Real-time physiological data is collected through wearable devices and IoT sensors and processed and feature extracted using big data technologies for early detection and accurate management of diabetes. The study shows that the system has a validation accuracy of 80% on the PIMA Indians Diabetes dataset, which is highly reliable and promising for application in diabetes prediction and management [8].

A comprehensive review of CGM sensor technologies and applications is presented [9]. The article provides a detailed review of the development of CGM technology and discusses the evolution of early prototypes and modern high-precision devices. Modern CGM devices, such as the Dexcom G6 and Freestyle Libre 2, have significantly improved glycaemic control, reduced the risk of hypoglycaemia and improved overall health management outcomes for people with diabetes through real-time monitoring and high-precision sensors. In addition, the article explores the use of CGM technology in clinical practice, particularly how it can help patients and physicians better understand and manage blood glucose fluctuations. The article looks at future directions for CGM technology, emphasizing seamless integration with smart devices and big data analytics to provide personalized medical advice and further optimize diabetes management [9].

3. Conclusion

With the continuous progress of medical technology, this research systematically introduces the latest progress and development trend of diabetes detection technology, focusing on the application and prospect of non-invasive detection technology, continuous monitoring technology and intelligent health monitoring system in diabetes management. Modern diabetes detection technology is developing in the direction of non-invasive, intelligent and multi-parameter integrated detection in order to improve the patient's testing experience and treatment effect. Non-invasive testing technologies are becoming mainstream, and these technologies not only reduce patient discomfort and pain, but also provide more convenient testing methods, such as skin patch sensors, wearable devices, and non-invasive glucose monitoring instruments, which greatly improve the patient monitoring experience. Among them, biomarker detection has also become an important development in the field of diabetes detection. Researchers are exploring new biomarkers to detect diabetes, such as specific metabolites in the urine or protein markers in the blood, and the detection of these biomarkers may be potentially valuable in early diagnosis and disease monitoring, providing new ideas and methods for the diagnosis and management of diabetes.

The development of continuous monitoring technology is also leading a new direction in diabetes management. Through the use of continuous glucose monitoring systems, patients can monitor changes in blood glucose levels in real time and make timely adjustments to their treatment regimens for better control of diabetes, and this technology not only improves the effectiveness of treatment, but also reduces the incidence of hypoglycemic and hyperglycemic events and improves the quality of life of patients. The rise of smart health monitoring systems has also brought new hope to diabetes patients. Combining technologies such as sensor technology, artificial intelligence and big data analytics, smart health monitoring systems enable personalized diabetes management, providing patients with customized advice and guidance to help them better control their blood glucose levels. These technological advances not only improve the accuracy and convenience of diabetes testing, but also provide patients with a more comfortable testing experience. In the future, with the continuous optimization of the technology and the promotion of clinical applications, these new tests are expected to play a more important role in diabetes management, improve patients' quality of life and bring new opportunities and challenges to disease management.

References

[1] Golparvar A, Boukhayma A, Enz C, et al. Rapid, sensitive and selective optical glucose sensing with stimulated Raman scattering (SRS). 2022 IEEE International Symposium on Medical Measurements and Applications (MeMeA). IEEE, 2022: 1-5.

[2] Zhao H, Wang F, Han Z, et al. Research advances on fiber-optic SPR sensors with temperature self-compensation. Sensors, 2023, 23(2): 644.

[3] Oliveira F A C, Dias F M, Toledo M A F, et al. Machine learning-based diabetes detection using photoplethysmography signal features. arXiv preprint arXiv:2308.01930, 2023.

[4] putra Selvia W L, Nurraharjo E. Alat pengukur kadar gula darah non-invasive berbasis arduino. Jurnal Informatika dan Rekayasa Elektronik, 2023, 6(2): 189-195.

[5] Mulyani D E, Maksum I P. Detection of biomarker using aptasensors to determine the type of diabetes. Diagnostics, 2023, 13(12): 2035.

[6] Sharma A, AlGhamdi W S, Faber H, et al. Non-invasive, ultrasensitive detection of glucose in saliva using metal oxide transistors. Biosensors and Bioelectronics, 2023, 237: 115448.

[7] Garg S K, Polsky S. Continuous glucose monitoring in pregnant women with type 1 diabetes. The Lancet, 2017, 390(10110): 2329-2331.

[8] AlZu'bi S, Elbes M, Mughaid A, et al. Diabetes monitoring system in smart health cities based on big data intelligence. Future Internet, 2023, 15(2): 85.

[9] Cappon G, Vettoretti M, Sparacino G, et al. Continuous glucose monitoring sensors for diabetes management: a review of technologies and applications. Diabetes & metabolism journal, 2019, 43(4): 383.