The utilization of diverse smart devices in the health management of diabetes patients

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Abstract. The utilization of smart devices in the management of diabetes has exhibited a significant upward trajectory. These devices aid in preemptively predicting the onset of diabetes, thereby fostering a more convenient and comfortable living environment for patients. However, there is a dearth of comprehensive literature reviews on smart device applications in diabetes management. A comprehensive review was conducted focusing on the utilization of smart devices for monitoring and optimizing diabetes management. The search was centered around relevant keywords including “diabetes”, “monitoring devices”, “self-care”, and “treatment tools”. The search process involved utilizing Web of Science, Google Scholar, and PubMed databases. The present paper examines the implementation of intelligent blood glucose monitoring devices and treatment equipment in diabetes management, encompassing aspects such as principles, usage methods, target populations, and efficacy. The utilization of smart devices in chronic disease healthcare provides significant convenience for patients with diabetes, enabling effective management and prevention of complications. Moreover, the integration of such devices enhances disease management efficacy and improves quality of life in patients.

Keywords: Diabetes, Glucose monitoring, Glucose control, Smart devices, Health management.

1. Introduction

Type 2 diabetes mellitus (T2DM) is a metabolic disorder characterized by persistent hyperglycemia resulting from insulin resistance or inadequate insulin secretion, which has high disability and mortality, and seriously affects the physical and mental health of patients and their families [1-3]. The presence of diabetes is often accompanied by a multitude of complications, including but not limited to diabetic cardiomyopathy, diabetic retinopathy, diabetic nephropathy, diabetic neuropathy, and diabetic foot ulcers [4]. According to the International Diabetes Federation in 2022, it is expected that China will become the country with the most diabetes patients in the world by 2045, with a total of 151 million patients [5]. As the aging process in Chinese society accelerates and lifestyles of residents change, it is expected that the incidence rate will further increase in the future [6]. And for patients with type 2 diabetes, 33.99% of their medical expenses need to be borne by their families during the course of treatment. This implies that the treatment of diabetes has incurred a significant cost for patients, their families, and society.

Consequently, there is an imperative for cost-effective and efficient strategies to manage, monitor, and treat diabetes. In recent years, the application of smart devices in diabetes health management has gained traction [7, 8]. In terms of diabetes monitoring, smart devices can make blood sugar monitoring operations more convenient and reduce the measurement time, which can reduce the time patients spend waiting for results in hospital and enable them to learn about their blood glucose dynamic changes in a timely manner, providing a basis for adjusting their glucose control plans[9]. In the treatment of diabetes, smart devices can also provide better treatment options, and can take a different approach in the treatment of diabetes by using high-tech means to open up entirely new treatment avenues, thereby improving the effectiveness of diabetes treatment and benefiting more patients. It is clear that intelligent devices can provide different treatment methods and have unexpected effects in medical treatment equipment [10, 11].

The innovation of this article lies in the following aspects: Firstly, this paper makes a systematic comparative analysis of the mainstream monitoring and treatment intelligent devices and nonmainstream new intelligent devices (such as wearable health trackers) in the market for the first time. Unlike previous studies, it provides a multidimensional comparison based on functionality, technological features, and patient needs. Secondly, a new contribution of this review is the proposal of a multidimensional framework for evaluating smart devices. This framework integrates technical performance, user experience, clinical efficacy, and data security results, addressing the lack of standardized evaluation criteria in existing literature.

2. Blood glucose monitoring equipment

Blood glucose monitoring is an important part of diabetes comprehensive management. The first-generation blood glucose meter needs to collect blood from the fingertip to detect blood glucose. The main principle of them are the determination by the electrode method. That is, under the action of coenzyme, the glucose dehydrogenase contained in the blood glucose test paper converts the glucose in the blood sample into gluconolactone, and the direct current generated during the reaction can be detected and converted into the corresponding blood glucose value by the blood glucose meter at the same time and displayed on the screen of the blood glucose meter [12]. The following blood glucose detection devices will be introduced from the aspects of applicable population and application methods.

Onetouch is suitable for patients with all types of diabetes. It can be used simply by taking blood from patients' finger with a blood sampling pen, holding the sample close to the sampling window, and waiting 5 seconds for a result. The meters are equipped with a ColorSure dynamic range indicator and employ an array of sophisticated automated algorithms to present insights and trends on the screen. The accuracy and reproducibility of the OneTouch in various glucose concentrates met standard acceptability. However, during the process of blood collection, there may be transient mild pain in the bleeding and at the site of blood collection, and very little syncope may occur [13].

ACCU-CHEK is suitable for patients with all types of diabetes, and blood samples are tested using dipsticks. The ACCU-CHEK is capable of displaying results within a matter of seconds, ensuring a rapid testing process. It has the capacity to automatically store up to 200 test results. Additionally, it can compute both 7-day and 14-day blood glucose averages, facilitating straightforward data analysis through its downloadable feature. However, the accuracy of the test results from commercially available Accu-Chek devices is generally questionable. In the Accu-Chek glucose meter group, continuous glucose monitoring readings showed good agreement with the hypoglycemia threshold; however, there was significant discrepancy between the glucose meter readings and the central laboratory values. The correlation analysis revealed that for both low and high glucose levels, the readings from the glucose meter deviated from the central laboratory analyzer by more than 10% over 61% of the time. Within the hypoglycemic range, discrepancies exceeding 20% were observed 57% of the time [14].

Ascensia CONTOUR is suitable for patients with all types of diabetes. It doesn't require much to measure blood volume, and it doesn't need to be too deep, it can be used by inserting the test strip, and it is fully automatic coding, eliminating many unnecessary steps. At the same time, Ascensia CONTOUR test strips are valid for 24 months, which can also be used after the test strip is opened. It also supports secondary sample adding, which will not be wasted. It is equipped with a large screen to display the readings, the elderly can also easily use it. At the same time, the device itself can store 480 sets of blood glucose records, which can provide accurate reference data for doctors in subsequent medical visits. Ascensia CONTOUR's test results were also accurate, with 100% of the system's results meeting accuracy requirements and 98.3% meeting the more stringent criteria [15]. It ranks among the best in the accuracy of many blood glucose meters, but it has few purchase channels and high price.

In addition to conventional glucose monitoring systems like glucometers, there is also a continuous glucose monitoring (CGM) system that employs the electrochemical glucose oxidase reaction for real-time glucose level assessment. After the sensor was implanted into the subcutaneous tissue, the glucose was filtered through a semi-permeable membrane to react with glucose oxidase to produce gluconic acid and hydrogen peroxide [16, 17]. The hydrogen peroxide was further decomposed to generate electrons corresponding to glucose. The glucose in the interstitial fluid can be converted into an electrical signal, and then calculated as the blood glucose value. The sensor is implanted in the subcutaneous tissue, enabling real-time detection of interstitial fluid glucose concentration, thereby facilitating continuous glucose monitoring.

The Guardian is a brand of continuous blood glucose detector. It is suitable for children, adults and adolescents. The Guardian system comprises a monitor, a glucose sensor, connecting cables, a Windows-compatible Com-Station for the storage of glucose readings, and a test plug to assess sensor functionality. Glucose sensor signals were sampled at 10-second intervals, with averaged readings logged and stored at 5-minute intervals. Additionally, the monitoring device has the capacity to retain blood glucose measurements for a period of up to 14 days. The glucose meter generated a dynamic blood glucose record every 5 minutes, with 288 records throughout the day. With a warning of high or low blood sugar, it is waterproof and can withstand water depths of 2.4 meters for up to 30 minutes. It also allows data sharing to physicians and the generation of various glycemic data reports. It can enable patients with diabetes or their physicians to adjust insulin dose and lifestyle based on blood glucose reports. Experimental data demonstrate that the Guardian system prevents 59% of low sensor glucose (SG) excursions and 39% of high SG excursions. The activation of predictive alerts substantially reduced the frequency of both low and high SG excursions. Without these alerts, the risk of experiencing low and high SG excursions was 1.9 and 3.3 times higher, respectively[18]. The mean glucose decreased by -3.0% ($p < 0.001$), and the standard deviation of glucose decreased (47.9 mg/dL to 41.5 mg/dL, $p < 0.001$). However, Guardian is a device with frequent blood glucose calibration, and finger blood is collected for each blood glucose calibration, so the user experience is not good.

Dexcom is suitable for patients with all types of diabetes, and the sensor can be worn on the back of the upper arm and the abdomen to detect blood glucose concentration. Glucose values obtained from Dexcom are provided at 5-minute intervals and can serve as a critical reference for diabetes management decisions. These data can also be integrated with devices from other manufacturers, including automated insulin delivery systems and multidose memory insulin pens, to enhance treatment efficacy. The Dexcom G7 has a smaller body-fitting component that improves patient comfort. If the receiver identifies any data gaps, it can also request up to 24 hours of missing data from the wearable component of the system to retrieve glucose values that were not successfully transmitted at the time of collection. Real-time remote monitoring is also available, which could be of great assistance to caregivers and guardians.Simultaneously, the measurement values obtained from the arms and abdomen were comparable to or exceeded those of other commercially available CGM systems. When worn on the arm or abdomen in adults with diabetes, the Dexcom G7 can be used accurately and safely for up to 10.5 days. In addition, Dexcom G7 has high accuracy and safety in monitoring blood glucose during pregnancy [19]. However, several studies have reported mild to moderate device-related adverse events in experimental settings. These events include possible moderate erythema at the insertion site, mild skin tears, and moderate erythema in the adhesion area. Additionally, there may be mild discomfort during sensor removal [20].

Free Style Libre H is available for adults with diabetes aged 18 years and older. The Free Style Libre H is worn directly on the arm, and the blood glucose results can be displayed by scanning. Free Blood glucose values can be immediately known, and can be dynamically monitored for 24 hours. Free Style Libre H is skin friendly and waterproof, so it is more comfortable to wear, and can check the effect of exercise on specific blood glucose values at any time [21]. The FreeStyle Libre H is equipped with an alarm system that alerts users to low blood glucose levels, thereby helping to prevent hypoglycemia. This feature can effectively reduce the incidence of hypoglycemic events in patients, particularly those with impaired hypoglycemia awareness or a fear of hypoglycemia and severe hypoglycemia. [22]. However, users need mobile phone scanning to obtain blood glucose data, which requires mobile phones with near field communication (NFC) function, and mobile phones without

NFC function need to purchase scanners. The sensor can only store data up to 8 hours and needs to be scanned over that period to preserve the data. At the same time, some users reported that the wear was not firm and easy to fall off in the last few days of service life, and the elderly had difficulty in using the registration.

3. Blood glucose treatment equipment

In addition to blood glucose monitoring systems, there are also a class of blood glucose treatment systems for the treatment of diabetic patients on the market, which are artificial pancreas and insulin pump. Artificial pancreas can be divided into two types: wearable artificial pancreas and implantable artificial pancreas [23, 24]. This article will introduce these three blood glucose treatment devices in detail from the aspects of principle, applicable population, use method, effect and clinical trial results.

Studies of a wearable artificial pancreas, which comprises an external insulin pump that wirelessly interfaces with a real-time continuous glucose monitoring system (CGMS) worn as a skin patch, are aimed at mitigating the incidence of nocturnal hypoglycemia. The Continuous Glucose Monitoring System (CGMS) measures blood glucose levels and transmits the data to a microprocessor for precise insulin dosage calculation. The insulin pump subsequently administers the calculated dose into the body, completing the therapeutic cycle [25, 26]. The wearable artificial pancreas is suitable for patients with all types of diabetes. Previous research has demonstrated that patients in diabetes camps who received treatment via an artificial pancreas system experienced significantly reduced instances of nocturnal hypoglycemia and achieved tighter glycemic control compared to those treated with a sensor-augmented insulin pump. Compared with sensor-augmented pump (SAP) therapy, the utilization of wearable artificial pancreas devices over a 12-week period resulted in improved glycemic control, a reduction in hypoglycemic events, and lower levels of glycated hemoglobin among adult patients. It has been proved that the clinical effect of wearable artificial pancreas is also improved compared to traditional insulin pumps [21]. Compared with sensor-enhanced pumps controlled by caregivers (SAP), the wearable artificial pancreas (AP) reduced hypoglycemia time by three times ($p < 0.001$) [27].

An implantable artificial pancreas (AP) system consists of an intravenous long-term enzyme sensor, an implantable insulin pump that delivers insulin to the peritoneum, and a controller with a proportional plus derivative control (PD) algorithm. The system is suitable for all types of diabetic patients and can be used when AP is implanted into the body. As for the advantages, the implantable artificial pancreas may address patients' fear of insulin injections, concerns about the risk of hypoglycemia, and difficulties with timely dose adjustments. Besides, it has been shown in clinical trials to be effective and safe for up to 1.7 years, with a lower risk of severe hypoglycemia than intensive subcutaneous insulin therapy. In a domestic pig experiment, the AP greatly reduced hyperglycemia without further manual insulin intervention [28]. On the other hand, AP are prone to inducing infection by causing disruption of the mucosal barrier and may compromise host defense mechanisms, leading to chronic infection or tissue necrosis when contaminated. At the same time, AP needs to improve the sensor structure to increase its service life and reduce sensor delay.

The insulin pump comprises four primary components: an artificial intelligence control system equipped with a microelectronic chip, a battery-powered mechanical pumping mechanism, a drug reservoir, and infusion tubing connected to subcutaneous infusion devices. During operation, the mechanical system of the pump, in response to commands from the control system, actuates the piston within the reservoir, ultimately delivering insulin to the subcutaneous tissue via the infusion line. It is suitable for patients with severe type 2 diabetes, diabetic women, diabetic patients who need major surgery, and diabetic patients with irregular life. The insulin pump is used in three steps: loading the insulin, connecting the catheter, and setting the parameters [29]. It is capable of mimicking the basal secretion of physiological insulin, thereby maintaining stable and normal blood glucose levels. It improves the life quality of patients. At the same time, it simplifies the injection and patients only need to change the input tube of the pump and only minimal insulin delivery during the night allowed the pump to reduce the risk of nocturnal hypoglycemia [30]. Clinical results demonstrated that after 6 months of insulin pump therapy, the mean interstitial blood glucose level decreased by 12.9 mg/dL (p=0.05) compared to multiple daily insulin injections. Notably, this therapeutic approach did not result in any significant adverse effects on the cardiovascular system [31]. Following a two-week course of insulin-pump therapy, the treatment group experienced a reduction in glycated hemoglobin levels such that there was no longer a significant difference compared to the control group post-intervention, whereas a substantial disparity existed prior to the intervention. Low density lipoprotein cholesterol levels in the experimental group were significantly reduced compared to those in the control group. However, the relatively high cost of insulin pumps may impose a significant financial burden on numerous families. At the same time, there is a certain risk of infection in the use of the insulin pump, and continuous puncture of the skin catheter may cause infection or skin reaction [32].

4. Innovative smart blood glucose devices

An increasing number of innovative smart blood glucose devices have reached a mature stage and hold promising potential to effectively serve individuals with diabetes in the future.

Smart contact lenses serve an essential function in the continuous monitoring of blood glucose levels. Due to the close relationship between the components of tears and blood (glucose, lactate, salt ions, etc.), blood glucose can be inferred based on the glucose in tears. Smart contact lenses are divided into fluorescent contact lenses, electrochemical contact lens light, optical diffraction contact lenses and so on. The smart contact lenses can be directly worn on the eyeball while being connected to an external device for data transmission. Monitoring blood glucose levels through smart contact lenses can effectively control the early stage and progression of diabetes. It has been observed that there is no significant difference between the tear glucose levels measured by fluorescent contact lenses worn on rabbit eyes and those measured by commercial blood glucose meters [33]. However, the current stage of smart contact lenses is not sufficiently mature, and there still exist some research challenges. On one hand, the material composition of smart contact lenses needs to exhibit excellent biocompatibility to ensure that prolonged wear does not result in ocular damage. On the other hand, it is imperative to guarantee optimal sensor-tissue interaction with tears as the glucose concentration in tears exhibits a certain correlation with blood glucose levels.

The principle behind smart socks lies in the correlation between foot temperature, pressure, and joint angle with foot ulcers. By analyzing data on foot temperature and pressure, relevant information regarding foot ulcer of patients can be obtained [34]. The smart socks are crafted with fibers containing five embedded fiber Bragg grating sensors, enabling the measurement of plantar temperature and pressure at specific anatomical locations including the big toe, first and fifth metatarsal heads, midfoot, and underfoot. These advanced socks have the potential to predict foot ulcer risks and can be utilized for efficient shoe fitting assessments in individuals with diabetes to alleviate plantar pressure. The temperature measured by the smart socks is relatively accurate and does not cause large deviations. The effects of smart socks were examined in a study, which revealed that the observed increase in foot temperature associated with smart socks was indicative of an inflammatory [35]. However, the electronic components and sensors in smart socks are prone to damage, and the internal structure of smart socks is relatively intricate, which may result in a firmer texture compared to ordinary socks and potentially compromise comfort.

The principle of smart insoles and intelligent socks for monitoring diabetes foot ulcers is similar. The clinical efficacy of smart insoles was demonstrated in a 34-week cohort study, where smart insoles accurately predicted 97% of future occurrences of diabetic foot ulcers [36]. The utilization of smart insoles enables clinicians to objectively categorize foot risk and deliver timely care, simultaneously, it can also mitigate the occurrence of foot hypertension [34]. However, the accessibility of such products remains challenging for individuals residing in remote areas, and there is a need for further enhancement in safeguarding the privacy of users.

The aforementioned content provides a comprehensive overview of the current blood glucose monitoring equipment, blood glucose treatment devices, and innovative intelligent devices available in the market. By integrating these smart devices, blood glucose monitoring data can be seamlessly combined with exercise and dietary information to enable real-time adjustment of insulin dosage or personalized recommendations for exercise and diet. The integration of telemedicine and smart devices in establishing a remote monitoring platform enables physicians to access real-time blood glucose data and health status of patients, facilitating the adjustment of treatment plans. This also involves the development of personalized smart devices catering to diabetic patients with varying degrees of disease.

The benefits of this review lies that it presents systemic advantages that contribute to the development of a knowledge system for the application of smart devices in diabetes health management. Additionally, it demonstrates timeliness by promptly reflecting the latest technology and application results in the field of intelligent equipment. Moreover, it offers guidance to medical professionals, serving as a valuable reference for making clinical decisions. In terms of limitations, the exploration of functional details is constrained. Given the necessity to encompass a wide range of smart devices, the depiction of specific functional applications for each device may only scratch the surface. Besides, there exists a delay in updates, and although this review benefits from timeliness, the process from research to writing and publication may hinder timely reflection of some cutting-edge smart device applications. Insufficient inclusion of dynamic collaborative application cases persists despite mentioning various smart devices.

5. Conclusion

In summary, this paper offers a detailed and comprehensive review of the smart devices employed in diabetes management, providing an extensive examination of their functionalities, applications, and implications. It covers a wide array of commonly available blood glucose monitoring and treatment devices, such as continuous glucose monitors, insulin pumps, and wearable health trackers, as well as innovative blood glucose management systems. The principles, usage methods, benefits, and limitations of each device are thoroughly detailed, providing readers with a clear understanding of their functionalities. Furthermore, this study integrates and analyzes data from various smart devices to comprehensively evaluate their technical capabilities, user experience, effectiveness, and overall impact on health management outcomes. The paper consolidates existing knowledge, providing a comprehensive foundation to guide future research and development in the field of smart devices for diabetes and blood glucose management. It highlights key advancements, and identifies gaps to inspire innovative solutions and improve patient outcomes.

In conclusion, this paper provides an in-depth and exhaustive overview of the smart devices utilized in diabetes management, offering a comprehensive exploration of their functionalities, applications, and implications. It covers a wide array of commonly available blood glucose monitoring and treatment devices, such as continuous glucose monitors, insulin pumps, and wearable health trackers, as well as innovative blood glucose management systems that leverage advanced technologies like AI and IoT. The principles, usage methods, benefits, and limitations of each device are thoroughly detailed. Additionally, this study integrates data from diverse smart devices to comprehensively evaluate their technical capabilities, user experience, and health management outcomes. The paper consolidates existing knowledge to guide future research and development in the field of smart devices for diabetes and blood glucose management.

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