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MODERN TECHNOLOGIES FOR GLYCEMIC MONITORING IN PATIENTS WITH DIABETES AS A TOOL FOR REDUCING HYPOGLYCEMIA AND ITS COMPLICATIONS – CLINICAL AND SOCIAL IMPLICATIONS

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ABSTRACT

Diabetes is one of the most serious health problems of modern times. One of its most dangerous complications is hypoglycemia, defined in most cases as a drop in blood glucose concentration below 70 mg/dl. Recurrent hypoglycemia is associated with a significant increase in patient mortality due to both injuries and cardiovascular and neurological complications. The fear of hypoglycemia alone sometimes paralyzes patients' daily lives. Technological advances have made it possible to replace flawed traditional methods of self-monitoring of blood glucose with systems that enable continuous glucose monitoring, which significantly reduce the frequency and duration of hypoglycemia.The latest methods not only allow for round-the-clock blood glucose monitoring, but also warn the patient of the risk of hypoglycemia based on continuous assessment of blood glucose trends, automatic modification of the insulin dose by the device based on current results, and remote monitoring of the patient by a doctor. The use of modern methods brings long-term socioeconomic benefits in the form of a reduction in the number of severe hypoglycemia episodes and, consequently, hospitalizations and their complications. In addition, CGM systems increase patients' sense of security and control over their disease. However, the use of the latest technological advances also presents challenges for patients in terms of their ability to use new technologies, as well as social and economic constraints that hinder the implementation of the latest treatment methods.

KEYWORDS

Diabetes Mellitus Type 1, Diabetes Mellitus Type 2, Hypoglycemia, Continuous Glucose Monitoring, Real-Time Glucose Monitoring

CITATION

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I. Introduction

Diabetes is one of the most serious health problems, affecting approximately 1 in 9 adults aged 20-79 and accounting for approximately 3.4 million deaths in 2024. The current number of people with diabetes worldwide is around 589 million, and this number is still growing—it is estimated that by 2050 it will reach around 853 million. [1] The incidence of diabetes is increasing regardless of its pathomechanism—this applies to both type 2 diabetes, which accounts for over 90% of cases [2], as well as type 1 diabetes, which primarily affects the younger population. [3] Hypoglycemia is both one of the most common and one of the most serious side effects of diabetes treatment, and its complications are associated with a significant increase in mortality among patients with diabetes. Its occurrence affects both the daily functioning of patients through temporary cognitive impairment and carries long-term cardiovascular and neurological complications. [4] [5]. Preventing hypoglycemia, especially in patients at risk of severe hypoglycemic episodes requiring third-party assistance, is a key element of diabetes treatment, as confirmed by the current trend toward less restrictive therapeutic targets for assessing carbohydrate metabolism control in this patient group. [6] Increasingly modern technologies used in healthcare allow for much better management of chronic diseases, which is particularly evident in the breakthrough in chronic glycemic control in patients with diabetes achieved by the advent of continuous glucose monitoring (CGM) systems. Traditional methods of self-monitoring of blood glucose (SMBG) used to date have had limited ability to detect asymptomatic hypoglycemia and have not always reflected actual blood glucose levels. [7] Unlike self-monitoring of blood glucose levels by patients using glucometers, the use of continuous glucose monitoring (CGM) systems allows for dynamic control of fluctuations in interstitial glucose concentrations. Through better blood glucose control, the CGM system reduces the risk of chronic complications and also reduces the frequency and duration of hypoglycemic episodes in both type 1 and type 2 diabetes patients. [8] [9] The aim of this paper is to highlight the breakthrough and opportunities offered by technological advances in the treatment of chronic diseases, using the example of preventing hypoglycemia, which is extremely dangerous for patients with diabetes. The paper considers not only the benefits for patients, but also the potential challenges associated with the ability to use new technologies, as well as the social and economic constraints that hinder the implementation of the latest treatment methods.

II. Methodology

The literature review was conducted using two primary databases: PubMed and Web of Science. The analysis included publications encompassing clinical trials, observational studies, and review articles. The following keywords were used to identify relevant studies: diabetes, continuous glucose monitoring, CGM, glycemic monitoring, hypoglycemia, glucose variability, and digital health technologies.

Specific inclusion criteria were applied during the selection process: original research articles and reviews addressing the role of modern glycemic monitoring technologies in diabetes management, particularly in the prevention and reduction of hypoglycemia and its complications; publications available in English; and studies involving adult patients with diabetes (both type 1 and type 2).

The following types of publications were excluded: studies focusing exclusively on pediatric populations, experimental animal studies, papers lacking full-text availability (e.g., conference abstracts).

III. Results

Hypoglycemia – Clinical and Social Consequences

The most common biochemical definition of hypoglycemia is a blood glucose concentration of <70 mg/dl (<3.9 mmol/l). [5] However, it seems that in relation to patients with diabetes, hypoglycemia should rather be defined in relation to the patient's current clinical condition. Based on the classification proposed by The International Hypoglycaemia Study Group, there are three levels of hypoglycemia: 1 - hypoglycemia alert - usually asymptomatic, requiring treatment to prevent symptoms; 2 - clinically significant - associated with impaired cognitive function and consciousness; 3 - severe - associated with cognitive impairment requiring assistance from third parties. [10]

In turn, the American Diabetes Association proposes a more complex classification of hypoglycemia in patients with diabetes based on clinical presentation: severe—cognitive impairment requiring assistance from others; symptomatic documented/non-severe (symptomatic self-correctable low glucose concentration); asymptomatic (detectable only by measurement); probably symptomatic (symptoms of hypoglycemia not confirmed by measurement); pseudohypoglycemia (symptoms of hypoglycemia present with normal blood glucose levels). [11] Hypoglycemia is both one of the most common and one of the most serious side effects of diabetes treatment, significantly affecting both the daily functioning of patients and causing long-term complications, primarily through its adverse effects on the nervous and cardiovascular systems. [10] Acute complications of hypoglycemia include accidents (including car accidents) and falls leading to injuries and fractures, most often caused by temporary cognitive impairment in the form of disturbances of consciousness, behavioral changes, or memory loss, as well as seizures and, in extreme cases, even coma. [5] In addition, activation of the sympathetic nervous system and a decrease in blood potassium concentration during hypoglycemia lead to hemodynamic disturbances and disruption of hemostasis, thus increasing the risk of heart attack, life-threatening arrhythmias, and sudden death. [5] [10] Deaths during acute episodes of hypoglycemia, including particularly dangerous nocturnal hypoglycemia, are rare, but account for a significant proportion of deaths in patients with type 1 diabetes under the age of 40. [10] Long-term complications of recurrent hypoglycemia are associated not only with a cumulative increase in cardiovascular risk, weight gain due to snacking for fear of hypoglycemia, progressive cognitive impairment, and accelerated development of dementia in susceptible patients, but also with psychological, social, and economic complications. The constant anxiety and stress experienced by patients and their families due to the risk of hypoglycemia reduces their quality of life, adversely affects interpersonal relationships, and imposes limitations on daily activities such as driving or working. [5] In addition, exposure to recurrent episodes of hypoglycemia leads to a decrease in patients' awareness of their occurrence, making them more vulnerable to episodes of severe hypoglycemia and death. [10]

Modern methods of blood glucose monitoring

Continuous glucose monitoring (CGM) is a method of continuously assessing glucose concentration in interstitial fluid using a sensor located in the subcutaneous tissue, a data transmitter, and a receiver that allows data on individual daily changes in the patient's blood glucose levels to be collected. [12] Despite the possibility of physiologically justified discrepancies, the glucose concentration in interstitial fluid is considered a good equivalent of blood glucose concentration, while at the same time reducing the number of finger pricks required when using traditional methods of blood glucose monitoring (self-monitoring of blood glucose - SMBG). [13] Initially, only systems that enabled retrospective data analysis (retrospective CGM) were available, but now there are also real-time blood glucose monitoring (rt-CGM) and intermittent scanning CGM (isCGM) systems, and some of them are also equipped with insulin pumps. [7] There are also many other classifications of CGM systems based, among other things, on differences in the method of reading interstitial glucose concentration or the type of material from which the sensor is made. The use of the latest materials and the least invasive measurement methods allows the sensor's lifespan to be extended from 7 days to a month, and sometimes even longer, as well as reducing the risk of potential infections. [12] From a clinical point of view, the most groundbreaking development in glycemic control has been the introduction of real-time CGM (real-time continuous glucose monitoring), which allows the current blood glucose concentration to be assessed in real time thanks to wireless data transmission to a reading device, which can be a patient's mobile phone configured with a sensor or a doctor's computer. Using dedicated applications and algorithms, it is possible to visualize changes in blood glucose levels using graphs, analyze trends with an assessment of the risk of hypo- or hyperglycemia, and enable remote assessment of blood glucose control by a physician. [14] [12] Flash glucose monitoring (FGM) systems, also known as intermittent glucose monitoring (isCGM), are also widely used. They consist only of a connected sensor and transmitter and a reading device that shows the blood glucose concentration only at the time of reading, but retains the ability to assess blood glucose trends over an 8-hour period. The advantage of these systems is their lower price, but they require patients to scan their blood glucose levels regularly and, unfortunately, most devices do not alert them to impending hypo- or hyperglycemia. [12] In addition, there are more and more CGM systems available on the market that are configured with automatic insulin pumps capable of independently adjusting the current insulin dose based on the patient's current blood glucose concentration, including hybrid closed-loop (HCL) systems. Recent reports show that these systems have a beneficial effect on reducing both hypoglycemia and hyperglycemia episodes, but they still require further development. [13] [15] The continued development of artificial intelligence and increasingly advanced technologies offers hope for further improvement of existing methods, with the possibility of implanting well-tolerated, long-lasting subcutaneous sensors in the future, reducing device costs, and enabling patients to better self-monitor their condition. [14]

The Impact of Modern Technologies on the Incidence of Hypoglycemia

Studies show that patients with type 1 diabetes are more prone to both mild and severe episodes of hypoglycemia during insulin therapy than those with type 2 diabetes, and that the main factor influencing their frequency is the long duration of the disease. [5] Since the introduction of the first blood glucose meters in the 1980s, blood glucose monitoring in patients has been primarily based on self-monitoring at home using electrochemical strips that provide information only about the current blood glucose level, without the ability to predict impending hypoglycemia or hyperglycemia and subject to error due to the measurement technique. [12] Continuous glucose monitoring (CGM) systems have significantly changed the approach to treatment and have now become a key and extremely effective tool not only in the fight against hypoglycemia, but also in better long-term glycemic control, especially in patients with type 1 diabetes. [8] The introduction of rtCGM (real-time continuous glucose monitoring) has not only enabled wireless collection of data on the patient's blood glucose levels on a continuous basis, but also, depending on individual settings based on an analysis of trends, to warn the patient in advance of impending hypo- or hyperglycemia. This information allows patients to modify their insulin dose themselves in good time, and in the case of the latest devices, automatic dose correction is possible. [12] The results of a meta-analysis conducted by Wang and colleagues showed that the use of CGM (continuous blood glucose monitoring) in patients with type 1 diabetes was associated with a significant improvement in HbA1c levels and a reduction in the number of episodes of severe hypoglycemia compared to patients using traditional methods of glycemic control (self-monitoring of blood glucose - SMBG). [7] A systematic review conducted by Jiao and colleagues also points to significant financial benefits resulting from the use of CGM in glycemic control in patients with type 1 diabetes, primarily due to a reduction in the frequency and duration of hypoglycemic episodes, as well as a reduction in chronic complications due to better control of blood glucose levels. [8] Furthermore, a meta-analysis and systematic review conducted by Jancev et al. shows that the use of CGM also improves HbA1c values and other glycemic parameters in patients with type 2 diabetes. [9]

Pharmacotherapy in Hypoglycemic States

Pharmacological management of hypoglycemia depends on its severity and on whether the patient is conscious. The primary goal is to rapidly restore normoglycemia and prevent complications.In cases of mild to moderate hypoglycemia (≤70 mg/dL) in a conscious patient, oral simple carbohydrates should be administered, most commonly 15 g of glucose. After administration, blood glucose should be rechecked after 15 minutes—this is known as the "15–15 rule."Guidelines emphasize that "pure glucose is the preferred treatment" (American Diabetes Association, 2024), as it has the fastest onset of action. [16]

For the management of severe hypoglycemia (a hypoglycemic event that requires assistance of another person), prompt administration of therapy is necessary. In the setting of unknown duration of hypoglycemia and no IV access, glucagon is the primary medication. Glucagon functions by promoting glycogenolysis to release glucose into the circulation. In addition, glucagon has been demonstrated to stimulate gluconeogenesis during prolonged hypoglycemia. Updated policy reflects the new mechanism of action by combining these important treatment considerations: glucagon is indicated for the treatment of hypoglycemia in patients who are unconscious or unable to consume readily available carbohydrates. [16]

In recent years, new forms of glucagon have been developed—intranasal formulations and ready-to-use autoinjectors—which significantly improve the accessibility of therapy in out-of-hospital settings and reduce the time to intervention. Studies indicate that modern glucagon preparations are as effective as traditional formulations, while being easier to use and more frequently administered by caregivers. [17] In hospital settings, the preferred method for treating severe hypoglycemia is intravenous administration of glucose, which allows for the immediate correction of blood glucose levels. However, an important clinical concern remains the risk of recurrent hypoglycemia, particularly in cases associated with long-acting medications such as long-acting insulin or sulfonylureas.

In such situations, prolonged patient observation and modification of therapy are necessary. It is emphasized that drug-induced hypoglycemia may be recurrent and prolonged, requiring increased clinical vigilance. [18]

In summary, the pharmacotherapy of hypoglycemia should be individualized and tailored to its severity, while also taking into account the risk of complications and recurrence. Advances in new glucagon formulations and therapeutic strategies related to glycemic monitoring significantly improve patient safety and the effectiveness of treatment.

Reduction of Hypoglycemia Complications through Innovative Technologies

The development of continuous glucose monitoring (CGM) systems has significantly contributed to reducing the frequency of hypoglycemic episodes, particularly in patients at high risk of hypoglycemia. Modern CGM systems enable not only real-time glucose readings but also trend prediction and the generation of warning alarms. Clinical studies have demonstrated that these technologies lead to a significant reduction in the time spent in hypoglycemia as well as in the number of severe episodes, confirming their key role in modern diabetology. [19] Randomized clinical trials have shown that the use of CGM results in a measurable reduction in the time patients spend in hypoglycemic ranges. For example, in a study involving older adults with type 1 diabetes, a significant reduction in hypoglycemia exposure was observed compared to traditional self-monitoring of blood glucose. [20] The authors emphasize that CGM "resulted in a small but statistically significant improvement in hypoglycemia," indicating a meaningful clinical benefit even in high-risk populations.

The implementation of CGM also contributes to a reduction in hospitalizations and emergency interventions. Although this effect is indirect, it results from improved glycemic control and earlier detection of potentially dangerous states. The literature highlights that hypoglycemia remains one of the main limitations of intensive insulin therapy, and its reduction allows for safer achievement of therapeutic goals. [21]

Thus, CGM serves both as a diagnostic and a preventive tool. Importantly, the use of CGM allows for improved metabolic control without increasing the risk of hypoglycemia. In the randomized GOLD trial, CGM use led to a significant reduction in HbA1c (by 0.43%) along with a decrease in the number of severe hypoglycemic episodes. [22]

Similar findings have been reported in other studies, where CGM enabled simultaneous improvement in glycemic control and treatment safety. The long-term health benefits associated with CGM use are linked to reduced glycemic variability and decreased exposure to hypoglycemic episodes. Studies have shown that improvements in parameters such as time in range (by 15–34%) and reductions in HbA1c (by up to 0.25–3.0%) translate into a lower risk of vascular complications. [19] Consequently, CGM represents a crucial component of strategies aimed at preventing long-term complications of diabetes.

Social and Psychological Aspects of CGM Use

The use of continuous glucose monitoring (CGM) systems has a significant impact on the psychosocial functioning of patients with diabetes. One of the most important effects is an increased sense of safety among both patients and their families. Continuous access to glycemic data and alarm systems reduces uncertainty related to sudden hypoglycemic episodes, particularly at night. As studies indicate, these technologies enable a faster response to changes in glucose levels, which translates into a greater sense of control over the disease. [19]

Another important aspect is the impact of CGM on reducing stress and fear of hypoglycemia. This fear is one of the main limitations of intensive insulin therapy and often leads patients to intentionally maintain higher glucose levels. Thanks to continuous monitoring and alert systems, patients can make more informed therapeutic decisions. The literature emphasizes that hypoglycemia "remains a major limiting factor in achieving satisfactory glucose control," and its reduction contributes to an improved quality of life. [21]

CGM also plays an important educational role. These systems provide patients with insights into the relationships between diet, physical activity, and glucose levels, thereby increasing health awareness. Studies show that this technology acts as a tool supporting lifestyle changes, enabling patients to better understand the course of their disease and manage their therapy more effectively. [19]

The social aspect related to access to CGM technology is also significant. Despite proven effectiveness, access to these systems remains limited in many countries due to costs and differences in reimbursement policies. The literature highlights that limited access to modern technologies may contribute to widening health inequalities, particularly among populations with lower socioeconomic status. The development of alternative, more affordable monitoring technologies (e.g., those based on physiological sensors and machine learning algorithms) represents a potential solution to this issue. [23]

In summary, CGM not only improves clinical outcomes but also influences the broader psychosocial functioning of patients. The reduction of anxiety, increased sense of security, and improved health education make these technologies an integral component of modern, holistic diabetes care.

IV. Discussion

The findings presented in this review highlight the multifaceted role of modern glycemic monitoring technologies, particularly continuous glucose monitoring (CGM), in reducing the burden of hypoglycemia and improving diabetes management. Hypoglycemia remains one of the most significant barriers to achieving optimal glycemic control, especially in patients treated with intensive insulin regimens. The evidence discussed confirms that CGM systems have fundamentally shifted the paradigm from reactive to proactive diabetes care.

One of the key strengths of CGM lies in its ability to provide continuous, real-time data combined with trend analysis and predictive alerts. This functionality enables early identification of impending hypoglycemia and timely therapeutic intervention. As demonstrated in multiple randomized clinical trials and meta-analyses, CGM use is associated with a reduction in both the duration and frequency of hypoglycemic episodes, as well as improvements in HbA1c and time in range. Importantly, these benefits are achieved without increasing the risk of hypoglycemia, which addresses one of the central challenges of diabetes treatment.

From a clinical perspective, the integration of CGM with advanced insulin delivery systems, such as hybrid closed-loop (HCL) systems, represents a significant advancement toward automated and personalized therapy. These systems not only enhance metabolic control but also reduce the cognitive and emotional burden associated with constant self-management. However, despite promising results, further research is needed to optimize algorithms, improve long-term reliability, and assess outcomes in broader and more diverse patient populations.

The review also underscores the importance of pharmacotherapy in the management of hypoglycemia. While technological solutions play a preventive role, acute treatment remains essential, particularly in severe cases. The development of new glucagon formulations, including intranasal and ready-to-use injectable forms, has significantly improved the feasibility of out-of-hospital management. These innovations complement CGM systems by providing rapid and accessible treatment options, thereby enhancing overall patient safety.

Beyond clinical outcomes, the psychosocial and societal implications of CGM use are highly relevant. The reduction in fear of hypoglycemia, increased sense of security, and improved quality of life reported by patients highlight the broader impact of these technologies. CGM also serves as an educational tool, promoting patient engagement and facilitating behavioral changes. Nevertheless, disparities in access to these technologies remain a critical issue. High costs and variability in reimbursement policies may limit their availability, potentially exacerbating existing health inequalities. Addressing these barriers should be a priority for healthcare systems and policymakers.

Finally, the rapid development of digital health technologies, including artificial intelligence and non-invasive monitoring systems, offers promising future directions. These innovations may further enhance predictive capabilities, reduce invasiveness, and improve affordability, thereby expanding access and clinical utility.

V. Conclusions

Modern glycemic monitoring technologies, particularly CGM systems, represent a cornerstone of contemporary diabetes care. Their implementation significantly reduces the incidence and severity of hypoglycemia, improves metabolic control, and contributes to the prevention of both acute and long-term complications.

The combination of continuous monitoring, predictive analytics, and integration with insulin delivery systems enables a more personalized and safer therapeutic approach. At the same time, advances in pharmacological treatment, especially the development of novel glucagon formulations, further enhance the management of hypoglycemic episodes.

Importantly, the benefits of CGM extend beyond clinical outcomes, positively influencing patients' psychosocial well-being, quality of life, and engagement in self-care. However, ensuring equitable access to these technologies remains a major challenge that requires coordinated efforts at both the healthcare system and policy levels.

In conclusion, the integration of innovative monitoring technologies with modern therapeutic strategies offers a comprehensive approach to reducing the burden of hypoglycemia and improving outcomes in patients with diabetes. Continued technological advancement, combined with efforts to increase accessibility, will be essential for maximizing their clinical and societal impact.

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