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The impact of advanced diabetes technologies on safety and glycemic control during exercise in individuals with type 1 diabetes

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Abstract

Background:
Type 1 diabetes (T1D) represents an increasing epidemiological challenge worldwide. In Europe, the fastest rise in T1D incidence is currently observed in the northern and central regions. Effective glycemic control remains crucial for preventing acute and chronic complications, particularly in physically active individuals.

Aim:
This study aims to evaluate the impact of modern technologies supporting intensive insulin therapy on glycemic regulation, with a special focus on their role during physical activity.

Material and Methods:

A comprehensive literature review was conducted analyzing the use of continuous glucose monitoring (CGM) systems and continuous subcutaneous insulin infusion (CSII) via personal insulin pumps. Emphasis was placed on their effects on metabolic control and the reduction of severe hypoglycemia risk compared to conventional treatment. The function of advanced hybrid closed-loop (AHCL) systems, such as the MiniMed 780G, was also examined in relation to exercise-induced glycemic fluctuations.

Results:

CGM systems enable predictive monitoring of glycemic trends, shortening the response time to imminent hypoglycemia by approximately 20 minutes during physical activity. The application of AHCL systems provides automated protection against intra- and post-exercise hypoglycemia through features such as the SmartGuard algorithm and temporary target adjustments. These technologies significantly improve metabolic stability, even under conditions of intensive training.

Conclusion:

The integration of advanced diabetes management technologies with regular physical activity offers a new standard in T1D care. This approach facilitates enhanced glycemic control and hypoglycemia prevention, supporting safer and more effective engagement in physical exercise.

Keywords: Type 1 diabetes; continuous glucose monitoring; insulin pump therapy; advanced hybrid closed-loop systems; physical activity; exercise; glycemic control; hypoglycemia prevention.

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Abbreviations:

AHCL – Advanced Hybrid Closed-Loop

AID – Automated Insulin Delivery

AUC – Area Under the Curve

BGM – Blood Glucose Monitoring

CGM – Continuous Glucose Monitoring

CSII – Continuous Subcutaneous Insulin Infusion

CV – Coefficient of Variation

HbA1c – Glycated Hemoglobin

HIIT / HIIE – High-Intensity Interval Training / High-Intensity Interval Exercise

MARD – Mean Absolute Relative Difference

MDI – Multiple Daily Injections

MICT – Moderate-Intensity Continuous Training

SMBG – Self-Monitoring of Blood Glucose

T1D – Type 1 Diabetes

TBR – Temporary Basal Rate

TIR – Time In Range

WHO – World Health Organization

Introduction

1.1. Definition

According to the World Health Organization (WHO), type 1 diabetes is a chronic autoimmune metabolic disorder characterized by the destruction of pancreatic beta cells, leading to an absolute insulin deficiency that necessitates lifelong exogenous insulin replacement therapy.[1]

1.2. Epidemiology

Every day, more than 1,000 people worldwide are diagnosed with type 1 diabetes, corresponding to over 500,000 new cases annually.[2] A consistent annual increase in the global incidence of type 1 diabetes of approximately 3% has been observed. In 2021[3], an estimated 8.4 million individuals worldwide were living with type 1 diabetes, and this number is projected to rise to between 13.5 and 17.4 million by 2040. Low- and lower-middle-income countries accounted for approximately 20% of the global population of individuals with type 1 diabetes and are expected to experience the greatest increase in disease incidence.[4]

The epidemiological situation in Europe reflects these global trends. Most European countries have reported an almost twofold increase in the incidence of type 1 diabetes over the past three decades.[5] Northern European countries have historically exhibited the highest incidence rates of type 1 diabetes. In contrast, Central European countries, including Poland, despite having historically lower incidence rates, currently demonstrate the most rapid relative increase in cases, gradually approaching the levels observed in countries with the highest incidence.[6]

In Poland, a sustained increase in the incidence of type 1 diabetes has also been observed among children aged 0–14 years. This trend is characterized by regular sinusoidal fluctuations and a relative deceleration in recent years.[7]

1.3. Treatment

Intensive insulin therapy remains a cornerstone of type 1 diabetes management and is implemented through multiple daily injections (MDI) or continuous subcutaneous insulin infusion (CSII) delivered via an insulin pump. This approach allows for the approximation of physiological pancreatic insulin secretion and improves glycemic control while reducing the risk of both acute and chronic complications. Clinical studies and meta-analyses indicate that CSII is associated with more favorable metabolic outcomes compared with conventional insulin therapy, underscoring its role as a standard of care in diabetes management.[8] [9]

In recent years, continuous glucose monitoring (CGM) systems have become widely adopted in the treatment of type 1 diabetes, enabling real-time tracking of glucose levels and detailed analysis of glycemic trends, thereby facilitating optimization of insulin dosing. Meta-analyses of randomized controlled trials have demonstrated that CGM use is associated with a significant reduction in glycated hemoglobin (HbA1c), an increase in time in range (TIR), and a decreased risk of severe hypoglycemia compared with traditional self-monitoring of blood glucose (SMBG).[10] [11] Further clinical evidence confirms that CGM improves glycemic control not only in adults but also in older individuals with type 1 diabetes, leading to reductions in HbA1c levels and the frequency of hypoglycemic episodes when compared with SMBG.[12] [13]

In the comprehensive management of type 1 diabetes, dietary optimization and regular physical activity remain equally essential components, contributing to improved glycemic stability, enhanced insulin sensitivity, and a reduced risk of metabolic complications.[14] [15]

2. Research materials and methods

A systematic review of the scientific literature was conducted using the Google Scholar, Scopus, and PubMed databases. The search strategy included keywords related to type 1 diabetes, continuous glucose monitoring, insulin pump therapy, advanced hybrid closed-loop systems, and physical activity. The analysis focused on peer-reviewed publications addressing glycemic control, hypoglycemia risk, and the physiological responses to exercise in individuals with type 1 diabetes using modern diabetes technologies. Particular attention was given to the credibility and impact of the journals in which the studies were published, as well as to the methodological quality of the cited evidence. To ensure the relevance of the findings to current clinical practice, priority was given to the most recent and up-to-date publications.

3. Results

3.1. Physical Activity and Type 1 Diabetes

Regular physical activity is a crucial component of comprehensive type 1 diabetes management, providing beneficial metabolic effects, enhancing physical performance, and improving glycemic control. Numerous clinical studies and meta-analyses indicate that participation in structured exercise programs leads to reductions in HbA1c levels and increases in time in range (TIR) in individuals with T1D.[16] [17] [18] [19] [20] [21] [22] [23]

Studies evaluating various forms of physical activity in adults with T1D have shown that regular exercise is associated with decreases in HbA1c, although the magnitude of the effect depends on the duration and intensity of the activity.[16] [17] In children and adolescents with T1D, regular physical activity lasting more than 24 weeks, including sessions exceeding 60 minutes, resulted in significant improvements in glycemic control and physical performance, particularly at higher exercise intensities.[18]

Both aerobic and interval training (HIIT), as well as resistance training, optimize blood glucose levels during and after exercise, improving TIR and reducing the risk of acute complications.19 Resistance training may produce smaller glucose drops during exercise but can lead to a prolonged period of post-exercise glycemic reduction, which is important for planning insulin therapy before, during, and after physical activity.[24]

Different forms of physical exertion in people with T1D significantly influence glycemic responses depending on the type, intensity, and metabolic context of the exercise. A meta-analysis of high-intensity intermittent exercise (HIIE/HIIT) interventions in adults with T1D reported an average decrease in glucose levels of approximately 1.3 mmol/L during exercise, although results were heterogeneous and strongly influenced by the timing of food intake relative to the exercise session. These findings highlight the importance of timing and context in exercise-related glycemic responses. Postprandial exercise generally reduces glycemia more than fasting exercise, and glycemic reactions to HIIE may vary substantially between individuals, emphasizing the need to plan exercise in the context of meals and insulin therapy.[25]

Another meta-analysis assessing the effects of HIIT on glucose metabolism demonstrated that both HIIE and moderate-intensity continuous training (MICT) are associated with postprandial glycemic reductions and a consequent decrease in insulin requirements, particularly in interventions of moderate duration. Differences between HIIT and MICT were not significant with regard to reductions in postprandial glucose area under the curve (glucose AUC).[26]

Furthermore, a randomized controlled trial examining the impact of a 12-week HIIT intervention in overweight or obese adults with T1D indicated that, although overall changes in HbA1c did not differ significantly between study and control groups, participants who adhered closely to the HIIT protocol achieved significant improvements.[27]

Regular physical activity, both aerobic and combined aerobic-resistance, exerts long-term beneficial effects on body weight, glycemia, and metabolic profile, as well as improving cardiorespiratory fitness and reducing cardiovascular risk factors in patients with T1D.[20][21][28] Moreover, real-world physical activity increases TIR and positively influences daily glycemic control, as confirmed by observational and randomized studies.[29][30][31]

3.2. Glucose Monitoring During Exercise

Traditional glycemic monitoring using a blood glucose meter (BGM) provides only point-in-time measurements, which are insufficient under conditions of dynamically changing metabolism during exercise. Continuous glucose monitoring (CGM) has revolutionized the management of exercise in type 1 diabetes by providing real-time insight into both the direction and rate of change of glucose levels.

A key advantage of CGM over BGM is its ability to provide trend information. While a glucose meter reports only the current glucose concentration, CGM systems use trend arrows to indicate whether glycemia is stabilizing, rising rapidly, or falling. Research demonstrates that access to these data allows athletes to take preventive action approximately 20 minutes earlier than when relying on clinical symptoms or routine BGM measurements, significantly reducing the time spent in hypoglycemia during training.[32]

3.3. Insulin Therapy During Exercise

The primary advantage of personal insulin pump therapy over multiple daily injections (MDI) during exercise is the ability to rapidly reduce or suspend basal insulin delivery. Patients using MDI maintain a constant concentration of long-acting insulin, which necessitates the consumption of significantly larger amounts of carbohydrates around exercise to avoid hypoglycemia. In contrast, pump users can decrease the basal rate at any time before starting a workout, allowing for safer training with lower intake of exogenous calories.[33]

The incidence of delayed post-exercise hypoglycemia is markedly lower in individuals using continuous subcutaneous insulin infusion (CSII). Randomized studies have demonstrated that programming lower basal insulin doses for several hours after activity is not feasible with MDI without increasing the risk of hypoglycemia or requiring additional carbohydrate intake. CSII uniquely enables adjustment of the insulin profile to the increased post-exercise tissue sensitivity to insulin.[34]

In marathon runners with T1D, personal insulin pump therapy has been associated with more stable blood glucose levels compared with MDI. Athletes using CSII experience fewer rapid glycemic fluctuations, which translates into improved sports performance and a lower risk of having to discontinue competition for medical reasons. This advantage arises from the fact that insulin absorption from a pump is more predictable than the absorption of large doses of long-acting insulin from subcutaneous tissue during intense muscular activity.[35]

Further analyses in long-distance runners indicate that the use of CGM enables maintenance of longer time in range (TIR) compared with individuals relying on blood glucose meter measurements. CGM users more frequently make minor dietary adjustments, preventing large glycemic excursions. In contrast, individuals using glucose meters more often experience swings from severe hypoglycemia to hyperglycemia following excessive carbohydrate intake in response to a low glucose reading.[36]

During intensive multi-day sports camps, hybrid closed-loop (AID) systems have demonstrated a significant advantage over MDI in maintaining TIR. Studies suggest that pump algorithms automatically respond to the increased insulin sensitivity resulting from cumulative fatigue, whereas patients on MDI often face the challenge of making substantial manual adjustments to basal insulin doses, which is associated with a high risk of error.[37]

An important comparative aspect of CGM systems is the so-called lag time, which arises because glucose is measured in the interstitial fluid rather than in capillary blood. Recent studies indicate that, although the glucose meter remains the “gold standard” for point-in-time glycemic measurements during very intense sprints, modern CGM sensors demonstrate a high correlation with laboratory results. The advantages of continuous CGM recording outweigh minor measurement inaccuracies, which in the case of a glucose meter could result in overlooking rapid glucose drops between individual measurements.[38]

Comparisons of these methods in the post-exercise period show that CGM systems are more effective in detecting nocturnal hypoglycemia. Physical activity increases insulin sensitivity for many hours after exercise. Patients relying on glucose meters would need to wake multiple times during the night to maintain glycemic control. CGM systems with alarm functions automatically predict and alert patients to impending hypoglycemia, which is not achievable with traditional glucose meters, thereby significantly enhancing safety and sleep quality in individuals with T1D following exercise.[39]

Despite these clear clinical benefits, practical considerations remain. Glucose meters are reliable under extreme temperatures or during activities such as diving, where CGM sensors may malfunction or detach due to sweat. Nevertheless, in overall assessments, athletes report that eliminating the need for finger-prick measurements during runs or cycling sessions is a key factor in increasing motivation for regular physical activity.[40]

3.4. Hybrid Closed-Loop During Exercise

The implementation of advanced hybrid closed-loop (AHCL) systems, such as the MiniMed 780G, currently represents the pinnacle of diabetes technology for supporting physical activity in individuals with type 1 diabetes. Clinical studies demonstrate that this system, through the SmartGuard algorithm, allows users to achieve a time in range (TIR) exceeding 75–80% even on days with high training intensity, representing a significant improvement over previous-generation systems.[41] A key protective feature is the "Temporary Target" function (maintaining glycemia at 8.3 mmol/L), which effectively minimizes the risk of intra-exercise hypoglycemia through early reduction of basal insulin delivery and automatic suspension of correction boluses.[42]

Recent meta-analyses highlight that the 780G system is particularly effective in preventing delayed nocturnal hypoglycemia resulting from increased post-exercise insulin sensitivity.[43] Data from real-world clinical practice also indicate that users of this system exhibit significantly lower glycemic variability and require interventional carbohydrate intake during exercise less frequently[44]. Furthermore, the advanced automation of correction boluses in AHCL systems enables athletes to adopt a more aggressive approach to high-intensity interval training, effectively counteracting hyperglycemia induced by surges of counter-regulatory hormones.[45]

4. Discussion

Recent research published over the last decade indicates that CGM is a valuable tool for supporting metabolic control in individuals with type 1 diabetes who engage in regular physical activity or sports. Compared with traditional self-monitoring of blood glucose, CGM not only enables more frequent glucose measurements but, more importantly, allows for real-time assessment of dynamic changes in glucose levels. This capability is particularly relevant during physical exertion, which is often characterized by rapid and unpredictable declines in glucose concentration.[46 47]

Both observational and randomized studies have demonstrated that individuals using CGM achieve significantly longer time in range during exercise and in the immediate post-exercise period, while simultaneously reducing exposure to hypoglycemia and hyperglycemia.[4748]A key mechanism underlying the superiority of CGM over conventional monitoring methods is the ability to track glucose trends and utilize alert functions, including predictive hypoglycemia alerts. These features enable timely dietary interventions or insulin dose adjustments before clinically significant declines in glucose levels occur, thereby substantially improving metabolic safety during physical activity.[49] [49]

Studies involving children and adolescents have further shown that the use of CGM trend information reduces the frequency of exercise interruptions and minimizes the need for prophylactic carbohydrate intake, promoting a more natural and less disrupted course of physical activity. This aspect is particularly important for long-term adherence to physical activity recommendations in individuals with type 1 diabetes.[50]

Another advantage of CGM is its ability to detect delayed post-exercise glycemic disturbances, including nocturnal hypoglycemia, which often remain unnoticed when relying solely on point glucose measurements.[48] This is of considerable clinical relevance, as late-onset hypoglycemia represents one of the major barriers to physical activity participation among individuals with type 1 diabetes. It should be noted, however, that CGM accuracy may slightly decrease during intense or highly dynamic forms of exercise, particularly under conditions of rapid glucose fluctuations. Nevertheless, the majority of studies indicate that CGM accuracy during physical activity remains clinically acceptable and sufficient to support therapeutic decision-making.[51]

5. Limitations

This study has several limitations that should be acknowledged. First, the analysis is based primarily on previously published literature, which may introduce publication bias and limit the availability of negative or inconclusive findings. Although efforts were made to include the most recent and high-quality studies, variability in study design, sample size, and outcome measures across the included publications may affect the comparability of results.

Second, differences in physical activity type, intensity, and duration, as well as individual variability in insulin sensitivity and metabolic responses to exercise, may limit the generalizability of the findings. The reviewed studies often involved heterogeneous populations with varying levels of diabetes self-management skills and access to advanced diabetes technologies.

Finally, while advanced hybrid closed-loop systems demonstrate promising benefits in reducing exercise-related hypoglycemia, long-term real-world data particularly in athletes engaged in high-intensity or competitive training remain limited. Further prospective and controlled studies are needed to better assess the long-term effectiveness and safety of these technologies in diverse physically active populations with type 1 diabetes.

6. Conclusions

In light of numerous scientific reports, physical activity should be considered an integral component of treatment for individuals with type 1 diabetes, tailored to the patient's age, health status, and individual needs, while simultaneously monitoring glycemia and adjusting insulin doses.

The contemporary epidemiological landscape of type 1 diabetes indicates a dynamic and concerning increase in incidence worldwide. In Central Europe, including Poland, this increase follows a rapid trend, gradually approaching the incidence rates observed in Scandinavian countries.

In response to these challenges, intensive insulin therapy supported by advanced technological solutions, such as personal insulin pumps integrated with continuous glucose monitoring systems, has become the cornerstone of modern therapy. Scientific evidence consistently demonstrates that the integration of these tools enables significant improvements in metabolic control, reflected in reductions in glycated hemoglobin and increases in time in range, while simultaneously decreasing the incidence of severe hypoglycemia. This technology is particularly important in the context of physical activity, which, although an essential element of treatment, carries a high risk of glycemic fluctuations depending on the type and intensity of exertion. Continuous glucose monitoring systems provide athletes with a predictive advantage through trend analysis, while personal insulin pumps equipped with modern hybrid closed-loop algorithms automate protection against hypoglycemia via temporary target functions and intelligent modulation of insulin delivery. By allowing precise basal rate reductions and mitigating the risk of delayed post-exercise hypoglycemia, these systems currently represent the most effective tools for enabling patients to safely engage in a range of training modalities, from aerobic exercise to high-intensity interval training.

Personalized therapy combining closed-loop insulin delivery, dietary management, and regular physical activity is becoming the new standard of care, optimizing clinical outcomes while significantly enhancing both the safety and quality of life of individuals with type 1 diabetes.

Supplementary materials

Not applicable

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Author contributions

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Mikołaj Patalong- formal analysis, resources

Bartłomiej Błaszkowski - formal analysis, resources

Mieszko Czapliński - investigation, data curation

Przemysław Kołodziej - resources, writing - rough preparation

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Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT (OpenAI) to improve grammar and language clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication

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