Continuous Glucose Dynamics Modelling and Closed-Loop Insulin Dosing Intelligence: Real-Time AI-Powered Tools for Diabetes Monitoring and Personalised Management

Dr. Seungjin Oh, Professor of Electrical Engineering, Pohang University of Science and Technology (POSTECH), South Korea

1. Introduction to Diabetes Management

The increasing prevalence of diabetes in non-communicable diseases has become a serious public health issue. Improper management of diabetes has led to a variety of complications and potentially serious diseases that can affect patients' lives. High blood pressure, high cholesterol, and high body fat are all related to the chronic hyperglycemia of diabetes. If not treated in time, it can lead to chronic diseases such as heart disease, stroke, kidney failure, nerve damage, circulatory disorders, and hypoglycemia. Regular blood sugar monitoring, in association with a healthy diet and regular physical activity, can help people with diabetes control their blood glucose. Blood glucose monitoring is a procedure for checking the risk of hyperglycemia or hypoglycemia. Self-monitoring blood glucose measures the current glucose concentration and is a function for immediate intervention.

Meanwhile, HbA1c reflects the severity of hyperglycemia in the past 60–90 days and is a long-term risk monitoring of diabetes-related complications. HbA1c only requires blood collection for blood glucose analysis within 5–15 seconds and is expressed as a value. The analysis is only processed by the human eye, its own instrument, and a non-invasive glucose sensor. The situation in China is comparable. The economic burden of diabetes in the rural areas of China is significant due to the lack of regular healthcare services and the lack of access to diagnostic technology to detect early signs of diabetes. The lack of infrastructure and information infrastructure development in rural areas has restricted the long-term management of farmers with T2DM. The reality of running legs for urban patients often hinders regular health examinations, and many urban patients

ISSN 2582 6921
Volume 5 Issue 6 [November - December 2024]

can only seek diagnostic services when they develop the disease to a serious condition. The cost of hospital expenses for patients with T2DM in rural and urban areas is very high, and the financial burden on patients and families seriously affects the quality of life of the population. The lack of regular blood tests and low blood glucose monitoring data rates for diabetic patients in rural and urban areas has increased the difficulty of diabetes management. It is not conducive to the iterative development and utilization of medical big data. High glucose levels are a potential factor for the risk of diabetes, so the daily regulation of blood glucose for patients with T2DM is very important. Patients should be aware of the fluctuations of the two glycolytic parameters of blood glucose levels over a period of time, which can inform the patient's medication regime and food consumption. In addition to regular medication, early detection of abnormal blood glucose data directly affects the one-year hospitalization rate. Implementing medical care requires people to use essentially intelligent, mobile personal glucose monitors. Glucose monitors can provide data that is consistent with clinical standards, which can be transmitted to blood sugar management and intelligent health programs, thus playing an extremely important role. Staff members of a medical institution's health center benefit mainly from this data because it embodies it.

1.1. Overview of Diabetes

Today, the capacity of artificial intelligence (AI) and data sources of relevant clinical information expand the prospect of engaging in real-time therapy in diabetes by bringing intensification, optimization, and coaching with the utilization of various machine learning techniques. Machine learning, based on unsupervised learning in diabetes data, capitalizes on the untangling of hidden sub-patterns, thus providing supervised learning with a much-refined data set for performance adaptations, for example, higher success targeted drug development, especially relevant in a world of expensive drug types, allowing transformative therapies targeted at the underlying characteristics of disease sub-phenotypes with the highest success. However, characterized disease patient sub-states based on glycemia cannot be observed by current common use in clinical practice continuous glucose measurements.

Diabetes is an unfortunately prevalent disease with well-understood long-term sequelae of chronic hyperglycemia, resulting in the prevalence of microvascular disease, neuropathy, retinopathy, and nephropathy. From a deep learning system realization point of view, diabetes is a much more challenging pathology to manage than hypertension or even cardiovascular disease because of many factors contributing to the interplay of sugar balance. The diabetes model automation highlights that in diabetes, glucose-lowering medications may not necessarily be beneficial in the long term to the patient. As a result, individualizing treatment to high now-low next options for the given personalized nature of time glucose level is totally required in diabetes; this is not so in hypertension, in which the more common high now-long term-high next medication principles indeed hold.

1.2. Importance of Effective Diabetes Management

Type 2 diabetes mellitus is a chronic condition that currently affects nearly 31 million individuals in the United States and 415 million adults worldwide. Those numbers are steadily increasing and are expected to balloon by around 25% by 2035. Those with type 2 diabetes (both diagnosed and undiagnosed) require long-term management in order to prevent complications such as cardiovascular disease and chronic kidney disease. One out of every two adults diagnosed with type 2 diabetes has uncontrolled levels of glucose in their bloodstream, leading to an increased risk of dangerous complications.

Diabetes places a significant burden on the healthcare system. In 2017, diabetes core treatment costs in the United States exceeded $100 billion. Complications from the disease, such as nephropathy, neuropathy, and retinopathy, plus other long-term care costs, have also placed significant financial and societal burdens on those with diabetes. These numbers are a direct result of the perpetually high levels of HbA1c and underscore the significance of the development of interventions that can reduce these numbers and shift the trajectory of diabetes management. Unlike many other chronic diseases, the day-to-day management and oversight of type 2 diabetes typically falls upon the patient, making patient empowerment and self-efficacy key determinants in the maintenance of health. Due to the gradual progression of the disease, experienced clinicians must rely heavily upon their patients to self-report symptoms, side effects, and other critical indicators for disease management.

2. Role of Technology in Diabetes Management

Technology has significantly changed the way people with diabetes can manage their condition. The wide array of technologies available - continuous glucose monitors, mobile apps for everything from blood glucose logging to carbohydrate counting, smart pens for insulin delivery, and digital tools for remote consultations with healthcare teams - all look set to continue burgeoning. There are many examples of doctor-led advancements in diabetes technology, but this focuses on those innovations not only enabled by, but indeed driven by, real-time AI. With so many AI and machine learning insights to mine, the challenge now is translating all these new advances into actionable advice for real patients and healthcare teams.

The efficacy of utilizing technology to aid diabetes management is not in question if the user is prepared to pay for and utilize it. Continuous glucose monitors, for example, are incredibly successful in both type 1 and insulin-treated type 2 diabetes at reducing time spent in hypoglycemia - and indeed changing glycaemic variability for the better. Their in-built alerts can save users from life-threatening low glucose events. Because they show glucose trends as well as current glucose levels, they can empower people with diabetes to adjust or curtail carbohydrate intake far more effectively than traditional blood glucose monitoring can. Their use has exploded during the pandemic due both to associated cost reductions and to the rise in awareness of the importance of remote monitoring. Studies have shown that those who adopt new methods, especially those with type 1 diabetes, who historically more readily embrace new interventions due to the seriousness of the condition - can derive significant benefits.

2.1. Evolution of Technology in Diabetes Care

Several pioneering companies have been working to create and advance AID technology over the years. Clinical studies have demonstrated that the use of this technology can improve glycemic control in adults, helping to keep them in the optimal glucose zone for longer. Each system uses different algorithms, which are predominantly regulator-based, in addition to machine learning methods that learn from previous inputs to control BGs. They are currently designed for patients with T1D and require patient interaction to perform a number of routine tasks that the patients are already used to completing multiple times each day, in order to input these into smart devices that then deliver the appropriate doses of required insulins.

DreaMed Diabetes recently received approval for their AID system and one of their main competitors, Diabeloop, is awaiting their final certification. However, in a similar way to the GLM system, these technologies have been carefully designed and manufactured to perform both data capture and predictive modeling steps. This makes the systems particularly appealing as treatment aids within chronic disease pathways, such as diabetes, where they can monitor glucose control and exchange information on a regular basis with patients and healthcare providers. This level of involvement ensures that this process is educationally enriching for all involved.

3. Fundamentals of Artificial Intelligence and Machine Learning

Artificial intelligence (AI) is defined as the science and engineering that develops intelligent systems or intelligent agents that can accomplish tasks in diverse fields. These tasks require sophisticated intelligent capabilities, including problem-solving skills, learning, adaptability, and communication or language understanding and use. AI techniques include symbolic reasoning, evolutionary systems, multi-agent systems, robotics, graphical neural networks, expert systems, fuzzy logic, and statistical approaches. AI has two practical perspectives: enabling novel applications and improving user experiences. Most AI applications require AI technology, where machine learning (ML) is currently the most prevalent technology due to its capability to analyze big data.

Machine learning and pattern recognition are closely related fields, where ML is one of the strongest areas of AI. Learning is a process of generalization from a set of examples, allowing the model to predict possible labels for new, unseen data by considering the relationships and inherent structure within the data. ML, like other AI techniques, has its roots firmly embedded in statistical modeling and data mining. Thus, problems that can be solved by standard statistical and data mining tools can also be solved by ML methods, although ML models may be more accurate in predicting future cases or assessing the influence of several variables on an outcome. In short, the main reasons ML is surpassing traditional statistical techniques are big data and advanced computing resources, enabling AI model development and evaluation. An AI system or model can not only analyze big data quickly but also generate smart information or knowledge directly and interactively.

3.1. Definition and Scope

Diabetes is a prominent chronic and multifaceted physical condition that arises from the inability of the pancreas to produce adequate insulin, insulin resistance, and problematically high blood sugar levels. This highly prevalent condition results in significant illness and mortality, as well as substantial healthcare expenditures.

Advances in technology, as well as public promotion of a healthy lifestyle, are effectively decreasing the occurrences of certain diabetes complications. Nevertheless, the progression of certain complications, hospitalizations, treatment regimens, and clinical conditions of diabetes and associated issues are significant both in terms of economic burden and human degradation. Their solution necessitates knowledge synthesis, communication of rapidly changing investigational data, and sound cognitive capability. Our proposed protocol creates a framework for monitoring and managing diabetes, utilizing real-time AI-powered systems and an adaptive, dynamic patient registry with algorithmically enhanced tools.

4. Integration of AI in Diabetes Management

Conclusions: Machine learning and AI integration into diabetes management tools can significantly improve glucose control, medication adherence, and lifestyle habits of patients with diabetes. As dependence on traditional in-person medical care decreases, real-time monitoring and self-management tools become more important. Although more research needs to be conducted on the efficacy of these tools, inherent benefits of using AI models, including real-time decision support, increased prevention of hypoglycemia and hyperglycemia, and data-based individualized recommendations, present significant advantages over traditional approaches to diabetes management. With careful integration to ensure cost-effectiveness and user-friendliness of AI interventions, the quality of diabetes care and patient outcomes can be significantly enhanced. Integrating AI into diabetes management tools allows for more patient-centered habits, contributing to the future of diabetes care in the virtual setting. Continuous glucose monitoring is one of the most important innovations in diabetes treatment. Recent technological advancements in sensors and communication devices allow real-time data to be directly collected and processed effortlessly from the patient. Closed-loop systems add another layer of automation-driven glucose control and respond almost immediately to the glucose levels detected. Despite the revolutionary outcomes derived from these and a variety of other closed-loop algorithms, each of them exploits a particular configuration of glucose control strategies, without the possibility of incorporating both individualized and knowledge-driven diabetes control rules.

4.1. Real-Time Monitoring Systems

Real-time monitoring is essential to enable individuals to manage their diabetes promptly and effectively. People with T1D are using various devices as standalone or linked devices. Regardless of the medical device combination that a person with diabetes is using, all the devices would normally be exchanging their information via Bluetooth, WiFi, or cellular, with a user interface receiving the data for a person to view or for a healthcare professional to review the data. An app associated with the receiver or mobile phone can be used to display the glucose data, medication reminders, and personalized coaching for medication adherence, meal planning, or physical activity. In many cases, the healthcare professional will receive remote monitoring data as well and sometimes be able to access the data through a secure website.

Real-time analysis on the phone enables immediate feedback to the participants. The information is also linked to coaching and decision-making support for different aspects of T2D management, i.e., meal planning, physical activity, medication adherence, glucose patterns, and trends. Artificial intelligence tools such as machine learning techniques are used to personalize hard-to-manage situations. Individual engagement is also crucial to increase participants' involvement and adherence. When coaching is not used, individuals with T2D can forget their diabetes. Principles of psychoeducation such as understanding, knowing, hoping, and acting are used to design easy-to-remember, convenient, and appropriate personalized advice. Providing options to participants, enabling them to build convenient virtual diabetic teams with health professionals and peers, sharing information with the target group, and using peer-led programs are other ways to increase adherence. Quizzes, polls, challenges, and games are used to learn from participants' interactions.

5. Impact of AI-Powered Tools on Glucose Control

The growing prevalence of diabetes, associated high levels of intervention, and proven benefits of strong glucose control give the field a strong incentive to embrace AI-powered tools for tracking key factors affecting glucose levels and providing patients with insights geared to facilitate improved glucose control and medication adherence. Our discussion within this subsection delves into the core points of this discussion. We start by offering a concise overview of the core systems potentially contributing to glucose control. We then lay out the framework of statistical learning at the core of most commercial diabetes management algorithms that drive these systems. Furthermore, we offer a description of systems that utilize reinforcement learning as their core engine. After offering a brief discussion of commercial systems built around these concepts, we delve into the potential benefits realized by patients and health providers by leveraging the capabilities of these AI-powered tools. We close by pointing out a selection of potential caveats and concerns in this realm. Our view is that, in sum, the uptake and widespread adoption of AI-powered glucose management tools is a public health opportunity that should not be wasted.

5.1. Continuous Glucose Monitoring

Continuous glucose monitoring (CGM) is the automated measurement of glucose in the body at regular intervals. It consists of sensors connected to a transmitter that collects and sends the glucose data to a receiver or smartphone. The sensors are inserted under the skin, usually on the abdomen, and stay in place for a week. After a week, a new sensor can replace the old one. With CGM technology, someone with diabetes can see the direction blood sugar is moving and verify if an insulin dose was correct, too high, or too low. CGM technology is saving people from a lot of finger pricks throughout the day because they can perform a finger-prick blood test to calibrate the sensors and check the accuracy less often. Continuous glucose monitoring produces a constant stream of glucose data, which provides insights into subtle glucose patterns. All of this data can be very difficult to manage on your own, but with the use of artificial intelligence, you can improve blood sugar control and real-time diabetes management without frequent finger pricks. AI can reveal improvements in glucose control through CGM metrics, which reveal glucose patterns that might have gone unnoticed. Specialized software can evaluate countless CGM metrics to provide specific details about your glucose data, such as time in range. Rather than reviewing these reports once a week or less, real-time personal AI can evaluate data and provide suggestions to improve your metabolic and diabetes health.

6. Enhancing Medication Adherence through AI

Currently, a number of commercially available AI-powered reminder and education solutions are available to support people with diabetes in their medication adherence. However, the availability of medication adherence solutions is not equivalent to the widespread use of such tools. There is still a need for modification and expansion of AI-powered solutions to make them more usable and effective for diverse patient populations. There is also a need to create a big data reservoir by promoting the widespread use of available AI-powered digital health solutions to improve medication adherence in patients with diabetes. Routine medication adherence supports blood glucose control, may prevent premature mortality, and delays or prevents diabetes-related complications for patients with diabetes. Barriers to medication adherence for patients with diabetes may include complex medication regimens, anxiety, depressive symptoms, or denial. To address patients' barriers to medication nonadherence, healthcare team members routinely educate or remind patients, provide counseling to normalize patients' concerns, and provide referrals to trained professionals. As healthcare digital health solutions have proven successful in digital education and reminders, diabetes patients can also be effectively supported in their medication adherence by using these technologies.

6.1. Personalized Medication Reminders

Patients are forgetful. It has been implied, given the association with appointment reminders and improved attendance and glycemic control. Personalized medication reminders, based on a patient's health record or physical mannerisms or calendar, have the potential to further aid patients in medication adherence. These reminders can cater to the patient's therapy, whether it be injectable, oral, or a medical process. They can encourage patients through intelligent language to pick up medications at the pharmacy or when they are out of low supplies at home. These tools rely on machine learning knowledge of the patient's adherence habits and can incentivize patients most at risk of non-adherence, whether it be cost of medications, schedules out of routine, or purchase barriers.

7. Lifestyle Adjustments and Behavioral Changes

Diabetes management, in particular, can benefit from a multifaceted approach that combines medication adherence and glycemic control with meaningful lifestyle changes. AI-powered real-time monitoring of patient physiological data, followed by personalized interventions and feedback, holds great potential in prompting these healthier behaviors. Dietary adherence and food intake, for example, are a central aspect of diabetes management, and remote food tracking could help significantly by providing patients with education, support, and personalized feedback. Food could be directly paired with glucose measurements to examine post-prandial glucose peaks and responses, allowing a more complete understanding of meal effects.

Exercise and physical activity are also crucial in managing diabetes, but measuring energy expenditure beyond merely counting steps is an ongoing challenge. Remote monitoring of physical activity could supplement patient records to enable more personalized and accurate determination of dietary and physical activity guidelines. This increase in awareness of the interrelationship among dietary intake, energy expenditure, and blood glucose measurements allows patients to make more well-informed choices. Smartphone-based applications working in the background of the platform can monitor physical movement, leverage motion-sensing localization algorithms, and initiate reminders to prompt patients to exercise if glucose levels tend to rise after a meal and physical activity levels have been low. Such highly tailored, context-aware prompts are more effective in spurring activity levels compared to generic reminders. Of course, physical activity tracking methods would be far more effective if they reported on intensive activities rather than merely simple stepping events. In the future, blood glucose monitoring could be combined with metrics related to respiration, perspiration, or skin temperature to draw richer inferences about patient activities and physiological metrics. In summary, insights related to dietary behavior and physical activity could be woven with additional feedback related to blood glucose and glucose algorithms, insulin dose determinations, and medication adherence, to reinforce patient education and management.

7.1. Diet and Nutrition Tracking

Several ML-based dietary intake assessment devices have been developed by combining image analysis, activity recognition, and food composition databases. analyzes three-dimensional data of food on the dining table using a mobile device and predicts the dietary nutrients within three seconds. tracks meals and physical activities by a wearable camera inside a round device fixed to a person's chest. uses a wearable camera to take images of food and trains dietary assessment models with manually assigned calories, nutrients, and weight, aim to automatically identify food images associated with nutritional information. Although use the same functions as the system, they focus on estimating health by using additional databases of disease diagnosis knowledge.

target large visual databases, while focus on tracking meals for elderly or office workers with wearable RGB cameras.

There are several challenges to developing efficient meal detection engines for diabetics. Generally, eating can occur at any moment of the day, and food types, meal quantities, and eating durations are diverse. People can eat at any time based on their habits, feelings, and relationships. Also, with strong experiences, people can consume food more quickly or slowly than others. reported an 85% recall and 84% precision. is a promising solution that caters to global users and is suitable for diabetic-centric meal detection with an accuracy complexity of a mean non-diabetes random sample community composition. Another popular image-based meal detection system reported an accuracy of 89% using a decision tree algorithm and a self-built database. However, only four types of meals and eight types of food nutrients are measured in the current system. In summary, most of the current food choice-assistive systems provide food choices and prohibited nutrients to improve management of blood sugar levels and insulin needs. Those proposed models are effective for food choices rather than meal detection for meal structure labeling and postprandial analysis.

8. Challenges and Future Directions

In the future, more non-invasive technology for glucose monitoring is likely to be developed, and as it becomes more available and practical, the synergy between continuous glucose monitoring and AI-powered decision support tools will enable the development of more powerful systems with the potential for even more significant improvements in glucose control with lower risks of adverse events. Moreover, it can be anticipated that these systems will offer options for highly individualized and flexible therapy and will empower patients with the knowledge and tools to manage their diabetes effectively. Providing the medical AI community with access to de-identified, non-identifiable patient data from a variety of different sensors and algorithms will help to address the complexities associated with clinical validation, allowing AI models to be trained and developed more efficiently while also reducing the potential for overfitting and health disparities. In addition to developing novel machine learning strategies that consider patient-level data and address specialist-specific needs, there is also an important need to provide education and training to medical specialists to ensure that they are comfortable and well-trained in using the technology. Furthermore, there are important decision-making, ethical, and regulatory considerations that are critical to creating an integrated development and approval pathway for AI systems for diabetes self-management. A careful consideration of the roles of patients, providers, regulators, and payers is essential to ensure that the emerging AI ecosystem delivers on the promise to improve patients' health effectively and safely. Taking these types of challenges into account from the beginning of the development cycle of AI-fueled digital health tools for diabetes will ensure that these systems are developed and tested in a highly responsible, compliant, and transparent way.

8.1. Ethical Considerations in AI-Powered Diabetes Management

The integration of advanced technology for diabetes and other chronic diseases can lead to improvements in patient outcomes and lower costs. However, associated ethical concerns must be addressed to ensure that these potential benefits are realized. These include the potential for disenfranchisement of the most vulnerable affected groups and consequences for relationships between healthcare providers and patients. The current healthcare system's focus on reimbursement and fee-for-service incentives creates a status quo centered on in-person care. It should rightfully enforce wins for key stakeholders on behalf of patients, providers, and health systems. However, when viewed through a patient-centered lens, the system can inadvertently produce problematic results. For example, wait times between appointments can last minutes on the phone and 30 to 45 days in person. This situation results in worse health outcomes, which increase health-related costs for patients living everyday life with diabetes.

The growth of AI technologies in models of care cannot be understated. The global machine-learning healthcare market is estimated to be about 1.18 billion U.S. dollars in 2017 and is expected to reach 19.25 billion by 2026. New technologies are infused with incredible promise, from acting as personalized chronic disease support apps to intelligent agents for primary and secondary health conditions. AI technologies require a rethinking of ethics to keep humans in the highest regard. Whether intelligent machines behave ethically or unethically, it all depends on how machine intelligence is programmed to understand the "why" and the end goal of a series of interventions to ensure knowledge of what it considers as acting in the best interests of a person. Ethical AI should always guide machines to obey the programmed rules to avoid unintentionally malfunctioning behaviors. This poses an additional level of consideration for anyone like a sensor-laden individual who is actively or passively engaged in remote health monitoring, and optimized systems rely on a complex machine-learning algorithm. Public health ethicists argue that there are other negative ethical AI externalities to an identification and recommend policy mechanisms managing risk to help induce appropriate fixes. A proper ethical framework can establish clear communication about the potential for self-triggered behavior changes while monitoring functionality, social choice, and personal data protection are taken into account.

9.. Conclusion

In conclusion, patients with diabetes need real-time analytic tools that can provide immediate feedback to help them make better lifestyle choices, optimize their glucose, and accurately analyze their glucose values. Machine learning's potential to offer predictive and prescriptive data analysis would lead to an explosion of these AI-powered tools because developers would have a new valuable source of data repositories. Perhaps more quickly than that, next-gen basic and advanced statistical process control diabetes device software would become a reality. These next-gen devices would require smaller arrays of CGM sensor fusion machine learning preprocessing to detect and correct real-time CGM random errors and minimize CGM forecast errors. Stakeholder and public policy concerns about the large novel machine learning-derived repositories of trended CGM and composite real-time health-type data need to be respected. Development and application of these predictive and prescriptive AI capabilities and machine learning sophisticated real-time control charts need to earn trust with unparalleled respect for patient and clinician ethical informed consent and the strictest privacy and confidentiality standards. It is not overstating the power and potential interest and importance of these AI predictive and prescriptive methods for general diabetes management, such as how to effectively integrate population health incentives, remote patient monitoring, telemedicine visits, and healthcare policy reforms. However, we hope that it is also fully clear that artificial intelligence tools and development work are at maximum advantage when they bolster clear testable empirical care improvement objectives. The ultimate determinant of application value is the realization of patients' improved outcomes for their personal diabetes care.