

Artificial Intelligence in Precision Diabetes Management: Towards Personalized and Equitable Care

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ABSTRACT

Artificial intelligence (AI) is transforming diabetes care across prevention, diagnosis, monitoring, and therapy personalization. Machine learning (ML), deep learning, and reinforcement learning approaches, combined with continuous glucose monitoring (CGM), closed-loop insulin delivery systems, electronic health records (EHRs), and multi-omics data, are enabling earlier detection, finer patient stratification, individualized therapeutic choices, and improved glycemic outcomes. Randomized trials and meta-analyses show that AI-enabled systems improve time-in-range (TIR), reduce hypoglycemia, and lessen treatment burden. However, challenges persist regarding data representativeness, model interpretability, regulatory oversight, equity, and clinical workflow integration. This comprehensive review synthesizes the current landscape of AI applications in precision diabetes management, with a focus on predictive modeling, CGM analytics, automated insulin delivery (AID), pharmacotherapy personalization, digital biomarkers, and digital twins. We also discuss implementation challenges, ethical considerations, regulatory frameworks, and future directions to ensure equitable deployment and sustained clinical impact.

Keywords: artificial intelligence, precision medicine, diabetes, continuous glucose monitoring, closed-loop systems

INTRODUCTION

Diabetes mellitus is among the most challenging chronic diseases of our time, affecting more than half a billion individuals worldwide[1–3]. Its prevalence continues to rise, with projections suggesting that by 2045, more than 780 million people will be living with the condition[4]. The economic and societal burdens of diabetes are enormous, driven by the direct costs of medical care, indirect costs from lost productivity, and the long-term complications that result when glycemic control is suboptimal. These complications, which include cardiovascular disease, nephropathy, retinopathy, neuropathy, and diabetic foot disease, account for substantial morbidity, mortality, and reduced quality of life[5, 6].

Traditional diabetes management has largely relied on generalized treatment algorithms that may not account for the heterogeneity of disease presentation, progression, and treatment response seen across individuals[7]. Type 1 diabetes (T1D) is an autoimmune-mediated destruction of pancreatic β -cells that results in absolute insulin deficiency, whereas type 2 diabetes (T2D) is characterized by varying degrees of insulin resistance, relative insulin deficiency, and progressive β -cell dysfunction[8–10]. Additionally, gestational diabetes and other specific types add to the complexity of this spectrum. This heterogeneity makes precision medicine an appealing approach to diabetes care, where therapy can be customized to an individual's genetic background, metabolic profile, environmental exposures, and behavioral patterns[11–13].

The growing availability of high-frequency, high-dimensional health data presents new opportunities for precision diabetes management. Continuous glucose monitoring (CGM) systems capture interstitial glucose every few minutes, creating a rich temporal dataset. Wearables provide additional streams of information on physical activity, heart rate, sleep, and stress patterns[14, 15]. Electronic health records store laboratory values, imaging data, medication histories, and clinician notes. Omics platforms add layers of genetic, epigenetic,

proteomic, and metabolomic information. Together, these data form a multidimensional portrait of the patient that, when properly analyzed, can inform individualized care decisions[16].

Artificial intelligence (AI) and machine learning (ML) methods are uniquely suited to analyze such complex data. Classical statistical methods often struggle to handle the high dimensionality, nonlinear relationships, and missingness that characterize real-world health data[17, 18]. By contrast, ML approaches—including supervised learning for prediction, unsupervised learning for clustering and subphenotyping, and reinforcement learning for dynamic decision-making can detect latent patterns and adapt to new data inputs. Deep learning models, such as neural networks and recurrent architectures, excel at modeling temporal dependencies in CGM time series, while gradient boosting machines and random forests remain powerful for tabular EHR data[19, 20].

The application of AI in diabetes is not merely theoretical. There are now commercially available hybrid closed-loop insulin delivery systems that use algorithm-driven insulin adjustments in real time. Smartphone-based decision support tools powered by ML can forecast hypo- or hyperglycemia and recommend preemptive actions[21]. Risk prediction algorithms are being integrated into clinical practice to identify patients at highest risk for complications, enabling early intervention. Early studies also suggest that AI-guided personalization of pharmacotherapy may optimize glycemic outcomes and reduce adverse effects[22].

Nevertheless, the road to widespread AI adoption in diabetes care is not without obstacles. The quality and representativeness of training data remain critical concerns, as models developed in one population may perform poorly in another. Interpretability of AI models is crucial to gain clinician and patient trust[23]. Regulatory frameworks must balance innovation with safety, ensuring that continuously learning systems remain reliable over time. Ethical considerations, including data privacy, fairness, and equitable access, must guide the development and deployment of these technologies[24, 25]. This review explores the state of the art of AI applications in precision diabetes management. It synthesizes current evidence, highlights clinical use cases, discusses implementation and equity challenges, and charts a roadmap for future research and policy directions. Our goal is to provide clinicians, researchers, and policymakers with a comprehensive understanding of how AI can be harnessed to transform diabetes care from a reactive, one-size-fits-all model to a proactive, personalized paradigm that improves outcomes at both the individual and population levels.

2. Methods

A narrative literature review was conducted by systematically searching PubMed, Scopus, and Web of Science databases from January 2015 to September 2025. Search terms included combinations of “artificial intelligence,” “machine learning,” “deep learning,” “precision medicine,” “diabetes,” “continuous glucose monitoring,” “automated insulin delivery,” and “pharmacotherapy personalization.” The search strategy was designed to capture both interventional and observational studies, as well as systematic reviews and meta-analyses. Articles were screened by relevance to the theme of AI in diabetes management, and preference was given to studies with robust methodology, large sample sizes, and real-world applicability. Data extraction focused on model type, input data modalities, clinical endpoints, performance metrics, and validation methods. The findings were synthesized narratively under thematic headings corresponding to different applications of AI in precision diabetes management.

3. AI-Driven Predictive Modeling and Patient Stratification

AI models have demonstrated superior accuracy in predicting incident diabetes compared to traditional regression-based risk scores. By integrating EHR data, laboratory parameters, family history, lifestyle factors, and increasingly, polygenic risk scores, machine learning algorithms can identify individuals at risk years before clinical onset[26]. Neural networks and gradient boosting approaches, for instance, have been used to derive risk models with higher sensitivity and specificity than conventional tools like the FINDRISC or ADA score. Such predictive capability enables targeted lifestyle counseling and pharmacologic prevention programs, which are more cost-effective than population-wide approaches[26].

Beyond risk prediction, AI enables the discovery of disease subtypes or endotypes through unsupervised learning methods. Clustering analyses have revealed distinct groups of patients with T2D who differ in their insulin resistance, insulin secretion capacity, age of onset, and risk for complications[27]. These subgroups exhibit differential responses to therapy; for example, those with predominant insulin deficiency may benefit more from early insulin initiation, whereas those with severe insulin resistance might respond better to insulin sensitizers. Identifying such phenotypes early facilitates a more rational selection of therapy, reducing the trial-and-error approach that is common in current practice[28].

AI-driven models also play a role in forecasting complications. Using longitudinal data, ML can predict progression to diabetic retinopathy, nephropathy, and cardiovascular events with a lead time of several years[29]. Early risk identification allows for intensification of glycemic, lipid, and blood pressure control, as well as closer surveillance, thereby potentially preventing or delaying complications. These models are being incorporated into clinical decision support systems, alerting clinicians when a patient crosses a risk threshold and prompting timely intervention[29].

4. Continuous Glucose Monitoring and AI-Enhanced Analytics

The proliferation of CGM has revolutionized diabetes management by providing near real-time data on glucose dynamics. AI methods are enhancing the utility of CGM by deriving clinically meaningful features such as time-in-range, glycemic variability, and rate-of-change patterns[30]. Deep learning approaches, including recurrent neural networks and temporal convolutional networks, can process these time series to forecast glucose levels up to two hours into the future. Accurate forecasting enables preemptive actions such as adjusting insulin dosing or carbohydrate intake to avert glycemic excursions[31].

AI-driven digital health platforms leverage CGM data to provide individualized decision support. For example, they can suggest optimal timing and dosing of prandial insulin, recommend exercise or dietary modifications, and provide behavioral nudges to reinforce healthy habits[32]. Such personalized feedback improves patient engagement and glycemic control, as demonstrated in multiple pilot studies[32].

At the population level, aggregation of CGM data analyzed through machine learning can help health systems identify patterns of suboptimal control and allocate resources more efficiently. For instance, patients with recurrent nocturnal hypoglycemia can be flagged for therapy adjustment or additional education[33]. These insights can inform quality improvement initiatives and public health planning.

5. Automated Insulin Delivery (AID) and Closed-Loop Systems

Automated insulin delivery represents one of the most tangible applications of AI in diabetes management, bridging real-time CGM data with insulin pump control to achieve near-physiological glucose regulation[34]. Early generations of closed-loop systems relied on proportional–integral–derivative (PID) controllers and rule-based algorithms. These approaches were effective in partially automating basal insulin adjustments but still required user input for bolus dosing, meal announcement, and exercise consideration[35]. Recent innovations leverage model predictive control (MPC) algorithms that forecast future glucose levels based on dynamic physiological models, adjusting insulin infusion proactively. The introduction of machine learning has enabled adaptive systems that learn from patient-specific data, fine-tuning parameters such as insulin sensitivity and carbohydrate ratios over time[36].

Clinical trials consistently demonstrate the superiority of AID over traditional sensor-augmented pump therapy. Randomized controlled trials have shown increases in time-in-range by 10–15%, reductions in HbA1c by up to 0.5–1.0%, and significant reductions in both severe hypoglycemia and hyperglycemia episodes. These improvements are especially notable in pediatric populations, who face significant challenges with glycemic variability. Furthermore, hybrid closed-loop systems are evolving toward fully automated bihormonal systems that deliver both insulin and glucagon[37]. These dual-hormone platforms are particularly promising for minimizing hypoglycemia risk during nocturnal hours and unannounced exercise, areas where single-hormone systems struggle.

In addition to glycemic efficacy, patient-reported outcomes show reduced diabetes-related distress and treatment burden when using AID systems[38]. However, challenges remain regarding device interoperability, cybersecurity risks, and algorithm transparency. Regulators such as the FDA have established frameworks for interoperable AID components, promoting innovation while ensuring safety. Future directions include incorporating real-time physiologic signals such as heart rate, galvanic skin response, and continuous ketone monitoring into control algorithms, further personalizing insulin delivery[38].

6. AI for Pharmacotherapy Personalization

Personalizing pharmacologic therapy in diabetes is increasingly feasible with AI-powered predictive analytics. Drug response to first-line agents such as metformin is heterogeneous, with up to 35% of patients failing to achieve adequate glycemic control. AI models that integrate clinical phenotypes, genetic variants (e.g., SLC22A1 polymorphisms affecting metformin transport), metabolomic profiles, and microbiome signatures can stratify patients according to the likelihood of therapeutic response[39]. Such stratification not only optimizes glycemic outcomes but also minimizes adverse effects and cost burden associated with ineffective treatment trials[39].

For insulin therapy, reinforcement learning algorithms are emerging as powerful tools for dose optimization. These models use patient-specific glucose–insulin response histories to iteratively refine basal and bolus recommendations. Pilot studies have demonstrated improved glycemic control and reduced hypoglycemia rates when reinforcement learning-guided dosing is used compared to clinician-derived regimens[40]. Beyond glucose-lowering, AI can facilitate polypharmacy optimization in patients with comorbid conditions such as hypertension, dyslipidemia, and chronic kidney disease. By integrating cardiovascular risk calculators, drug–drug interaction databases, and real-world outcomes, AI systems can propose safe and effective therapeutic combinations tailored to individual risk profiles[40].

7. Digital Biomarkers and Digital Twins

The digital revolution in diabetes care extends beyond glycemic monitoring to capture a wide array of physiologic and behavioral data streams. Wearables, smartphones, and implantable sensors continuously collect data on physical activity, sleep quality, heart rate variability, stress markers, and dietary intake[41]. AI algorithms transform these heterogeneous data points into actionable digital biomarkers that reflect metabolic

control, adherence, and risk of future complications. For example, passive data collection can detect early signs of nocturnal hypoglycemia through subtle changes in heart rate variability, triggering predictive alerts[42]. Digital twin technology represents a cutting-edge approach wherein a computational model of an individual's glucose–insulin dynamics is created. These virtual patient models are calibrated with real-world clinical and behavioral data, enabling simulation of therapeutic interventions before implementation[42]. Clinicians can test different insulin regimens, dietary patterns, or exercise protocols within the digital twin environment to predict glycemic outcomes, thereby reducing trial-and-error in real patients. This paradigm also enables in silico clinical trials, accelerating research and reducing costs.

8. Implementation and Equity Considerations

While AI-enabled tools promise to democratize precision diabetes care, their benefits will not be fully realized without addressing implementation barriers. Data quality remains a key issue, as models trained on homogeneous populations risk poor performance in underrepresented groups[43]. External validation across diverse racial, ethnic, and socioeconomic backgrounds is crucial to avoid perpetuating health disparities. Equally important is clinician and patient acceptance. Black-box models that cannot be explained or justified may face resistance[43]. Therefore, explainable AI approaches that provide interpretable reasoning for recommendations are vital for integration into clinical workflows.

Economic considerations cannot be overlooked. Advanced CGM sensors, insulin pumps, and AI-powered platforms remain prohibitively expensive in many low- and middle-income countries[44]. Scalable solutions leveraging smartphones, cloud-based decision support, and affordable sensors are needed to ensure equitable access. Policymakers, payers, and industry stakeholders must collaborate to create reimbursement models and infrastructure support for widespread adoption.

9. Ethical, Legal, and Regulatory Issues

The increasing use of AI in clinical decision-making raises critical ethical and legal questions. Patient data privacy is paramount, particularly when integrating EHR, wearable, and genomic information. Secure data storage, encryption, and compliance with regulations such as GDPR and HIPAA are essential. Algorithmic bias, if unaddressed, can exacerbate existing disparities[45]. Continuous auditing, model retraining, and transparent reporting of performance metrics across subpopulations are recommended safeguards.

Liability is another concern if an AI system makes a dosing recommendation that results in harm; responsibility must be clearly defined among the developer, clinician, and healthcare institution[46]. Regulators are beginning to address these complexities, with the FDA's Software as a Medical Device (SaMD) framework serving as a template for oversight. Adaptive AI systems that evolve with incoming data present unique regulatory challenges, necessitating frameworks for monitoring performance drift and ensuring ongoing safety[46].

10. Challenges and Limitations

Despite substantial progress, AI deployment in diabetes care faces challenges. Model generalizability outside the training dataset remains limited, leading to potential performance degradation in real-world settings. Data fragmentation across health systems and devices impedes seamless integration. Interpretability remains a tension point, as the most accurate deep learning models often lack transparency. Finally, patient behavior itself is dynamic, and changes in lifestyle, adherence, and physiology can shift data distributions, requiring continuous model adaptation.

11. Future Directions

Future research will focus on multimodal integrative models that combine clinical, omic, imaging, and behavioral data to refine patient stratification and therapeutic targeting. Federated learning approaches will allow AI models to be trained across multiple institutions without sharing raw data, improving generalizability while preserving privacy. Lightweight edge AI algorithms capable of running on wearable devices and smartphones will enable real-time decision support in remote or resource-limited settings. Moreover, regulatory frameworks must evolve to support continuous learning systems that can update safely as new data accrue.

CONCLUSIONS

AI-enabled precision diabetes management is transitioning from research into routine care, delivering measurable improvements in glycemic outcomes, quality of life, and clinical efficiency. To fully harness its potential, stakeholders must address issues of data diversity, interpretability, cost, and regulatory oversight. Multidisciplinary collaboration among clinicians, data scientists, patients, and policymakers will be essential to ensure that AI-driven solutions are safe, equitable, and widely accessible, ultimately advancing the goal of individualized and population-level diabetes control.

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