

The future and innovation of diabetes treatment

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Abstract. Diabetes, a widespread chronic disease, presents significant obstacles for individuals and healthcare systems globally. Effective management of this condition relies heavily on accurate diagnosis, appropriate treatment, and the use of sophisticated medical devices. In this article, we explore the dynamic realm of diabetes management, examining the evolution of diagnostic and treatment approaches towards more precise and individualized solutions. Attention will then be turned to the crucial role that electrochemistry plays in transforming diabetes treatment, particularly through the development of advanced glucose monitoring and insulin delivery technologies. These innovations not only improve the lives of people with diabetes but also highlight the vital significance of electrochemistry in the field of medical science. Furthermore, we will traverse the intricate world of medical equipment, categorizing and analyzing the distribution hurdles that affect the global availability and effectiveness of diabetes care. By interlinking these related topics, our goal is to present an all-encompassing view of the present and future prospects of diabetes management, emphasizing both the technological progress and the persistent challenges in providing equitable healthcare access.

Keywords: Diabetes Management, Electrochemistry, Glucose Monitoring, Insulin Delivery, Healthcare Access

1. Introduction

In the realm of endocrinology, diabetes mellitus stands as a prominent chronic disease, characterized by its impact on insulin secretion and function, resulting in elevated blood glucose levels [1,2]. This condition, affecting a significant portion of the global population, leads to prolonged hyperglycemia that can inflict damage across multiple organ systems, leading to an array of complications [2-4]. The complexity of diabetes is further underscored by its classification into four main types, each with distinct pathophysiological characteristics and management strategies [5,6].

Type 1 diabetes, predominantly diagnosed in children and young adults, is an autoimmune condition marked by the pancreas's inability to produce sufficient insulin, necessitating external insulin administration [7,8]. Conversely, Type 2 diabetes, more prevalent in the adult population, is characterized by insulin resistance and relative insulin insufficiency [6,8], with treatment modalities ranging from oral hypoglycemic agents to injectable insulin therapies [9,10]. Gestational diabetes, a transient hyperglycemic state observed during pregnancy, presents increased health risks for both mother and offspring [11], and is a harbinger of heightened risk for developing Type 2 diabetes in later life [2,11]. Additionally, other specialized forms of diabetes exist, resulting from genetic anomalies, pharmacological agents, endocrinopathies, and other etiological factors [12-14].

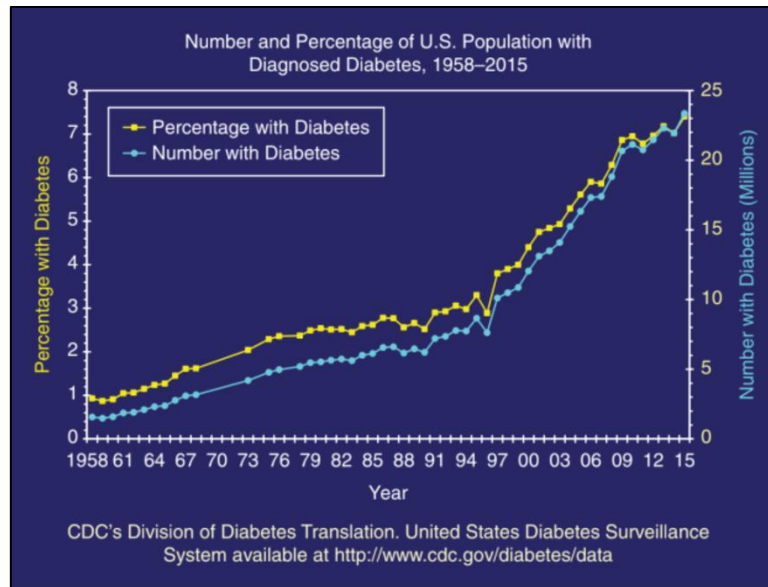


Figure 1. The number of people with diabetes is increasing year by year.

Central to the pathogenesis and management of diabetes is insulin, a peptide hormone synthesized by the pancreatic beta cells, encoded by the *INS* gene [15,16]. Insulin's pivotal role in regulating carbohydrate, lipid, and protein metabolism is achieved through its facilitation of glucose uptake and utilization in hepatic, adipose, and muscle tissues [1,8,15]. The secretion of insulin by beta cells is finely tuned to the body's fluctuating glucose levels, ensuring homeostatic control [1,15].

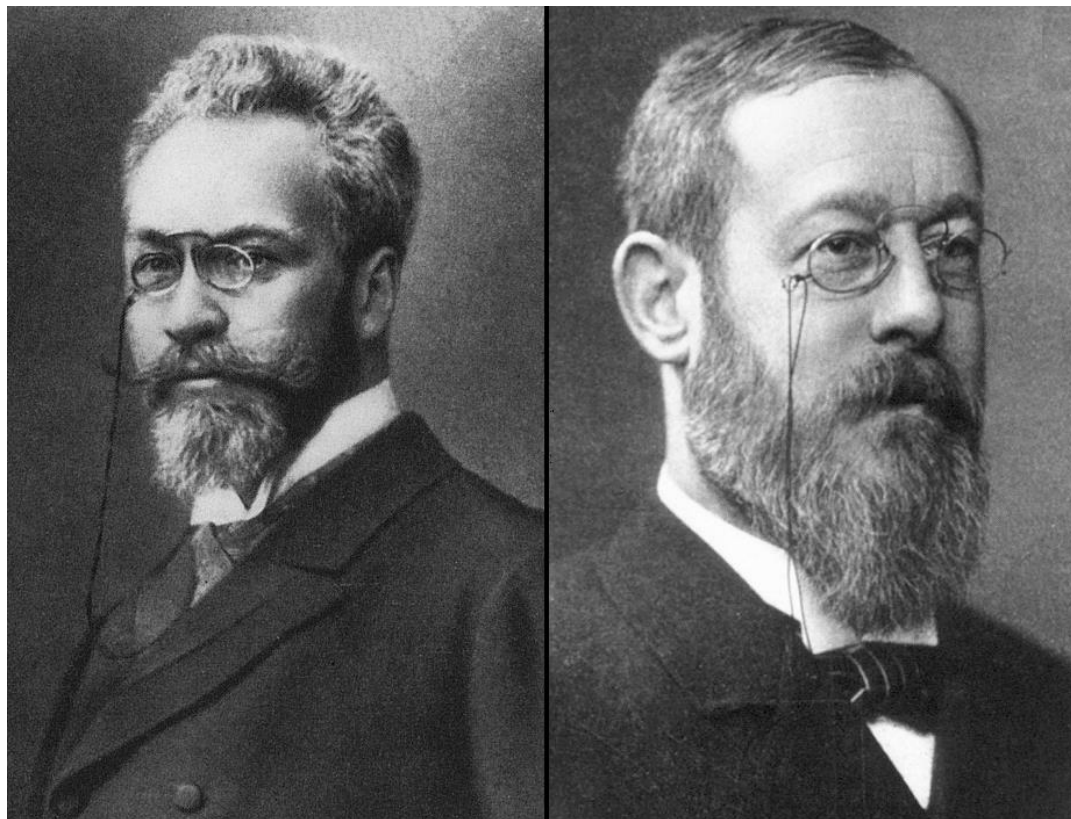


Figure 2. Oskar Minkowski (left) and Josef von Mering (right).

The historical journey to understanding the integral role of the pancreas in diabetes began with the groundbreaking experiments of Minkowski and von Mering in 1889, who postulated the pancreas's role in metabolism following their observations of diabetes induction in pancreatectomized animals [12,13]. This line of inquiry reached a pivotal moment in 1921 when Frederick Banting, a surgeon from Toronto, successfully decreased blood glucose levels in diabetic dogs using a pancreatic extract [14]. The isolation and subsequent characterization of insulin in May 1922 marked a revolutionary advance in the field, laying the foundation for modern diabetes treatment and research [16].

Medical devices are integral in managing diabetes, serving both monitoring and treatment functions. Blood glucose monitors, pivotal for tracking blood sugar levels, inform patients' dietary choices and insulin administration [9,17]. Insulin delivery, crucial in managing type 1 and type 2 diabetes, is facilitated through various means such as syringes, pens, and pumps [7,10]. Continuous Glucose Monitoring (CGM) systems provide real-time glucose data, minimizing the frequency of skin pricks and enhancing treatment precision [18,19].

Comprehending the classification and operational principles of medical equipment is crucial for enhancing diabetes management. Such understanding paves the way for synthesizing data from various devices, fostering the development of a scientifically robust and comprehensive system for glucose regulation [15, 16]. This approach aims to optimize treatment efficacy through a more integrated and informed use of technology [20,21].

2. Diagnosis and Treatment of Diabetes

Diabetes manifests in various forms, with type 1 and type 2 being the most prevalent. Other less common types include gestational diabetes, which occurs during pregnancy, and monogenic diabetes, a rare form caused by gene mutations. Additionally, secondary diabetes arises as a complication of other medical conditions. Each type has distinct characteristics and requires specific management strategies [5].

Diabetes occurs when the pancreas fails to produce sufficient insulin, a hormone crucial for blood sugar regulation. This deficiency necessitates exogenous insulin therapy. Insulin, synthesized by beta cells in the pancreatic islets of Langerhans, facilitates glucose uptake by body cells. Upon carbohydrate consumption, they are metabolized into glucose, elevating blood sugar levels. The pancreas normally responds to this increase by releasing insulin into the bloodstream, thereby maintaining glucose homeostasis [1].

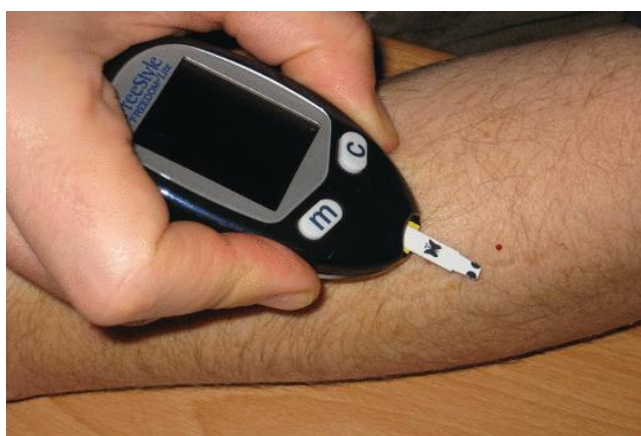


Figure 3. Patients use a glucometer to test their blood sugar.

Insulin, a key hormone, orchestrates several critical functions:

Blood Sugar Regulation: Insulin lowers blood glucose levels by facilitating its transfer from the bloodstream to cells, particularly muscle and fat cells. This action enhances glucose transport across

cell membranes for energy utilization or storage. In type 1 diabetes, the deficiency of insulin leads to increased blood glucose levels due to impaired cellular uptake [16].

Glycogen Synthesis: Insulin prompts liver and muscle cells to transform excess glucose into glycogen, a storable form of glucose. This conversion occurs post-meals when blood sugar is high. Conversely, insulin regulates glycogen breakdown, balancing blood sugar levels and preventing extremes like hyperglycemia or hypoglycemia [16].

Fat Metabolism: The hormone drives the conversion of glucose into fatty acids, facilitating the storage of excess glucose as fat in adipose tissue. It simultaneously inhibits fat breakdown and the release of fatty acids into the bloodstream [6].

Protein Synthesis: Insulin aids protein metabolism by boosting cellular amino acid absorption and stimulating protein synthesis, essential for tissue building and repair, including muscle growth.

Insulin plays a vital role in regulating glucose and energy metabolism. In scenarios where insulin is deficient or its utilization is impaired, as in diabetes, blood sugar levels can escalate abnormally, potentially leading to numerous health complications. Specifically, patients with Type 1 diabetes experience abnormal blood sugar levels due to an insulin deficit [8]. To rectify this, insulin injections are necessary, necessitating the use of various medical devices to administer and monitor treatment effectively [10]. This process is crucial for restoring and maintaining normal blood sugar levels in these patients.

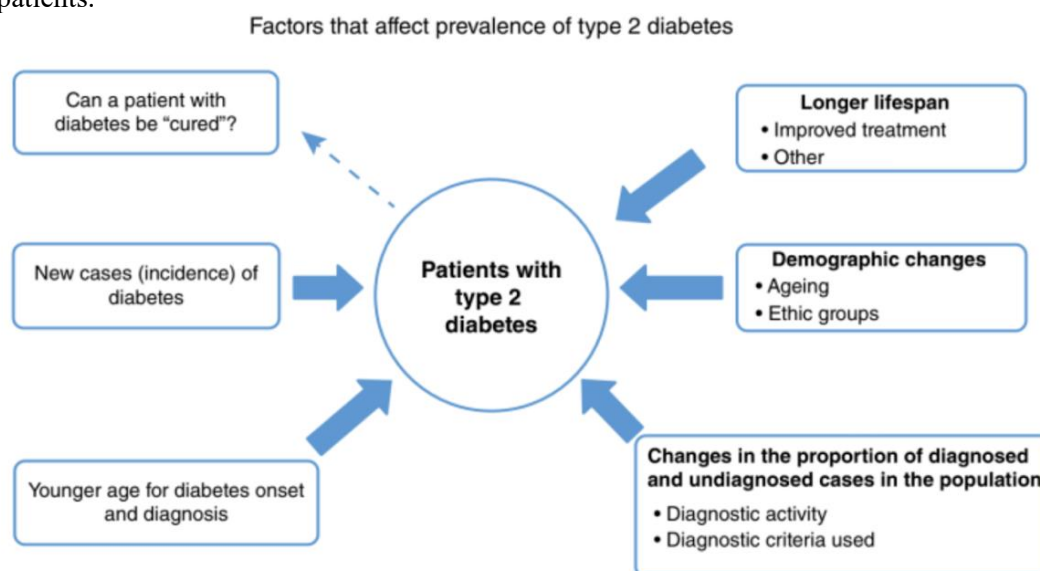


Figure 4. The future and innovation of diabetes treatment

3. The role of electrochemistry in the treatment of diabetes.

The management of diabetes, a multifaceted healthcare challenge, requires precise diagnosis, effective treatment, and continuous monitoring. Recent advancements in electrochemistry have significantly transformed this domain by introducing cutting-edge techniques for blood glucose monitoring and insulin delivery [12,13]. This essay examines the profound impact of electrochemistry on diabetes care, focusing on its role in enhancing patient care and improving clinical outcomes. The transition from conventional methods to modern, technology-based approaches marks a notable progression in patient treatment. Electrochemistry's critical contribution in refining glucose monitoring and insulin delivery systems has increased accuracy, efficiency, and overall quality of life for diabetic patients [9,17]. This shift towards electrochemical solutions represents a significant evolution in diabetes management, underscoring the importance of technological innovation in healthcare.

Electrochemistry, a branch of chemistry, delves into the interaction between electrical and chemical processes, primarily focusing on the transformation of chemical energy into electrical energy through redox reactions [14]. These reactions involve the transfer of electrons, with reduction and oxidation

corresponding to electron gain and loss, respectively. The resultant electric current from electron flow is utilized in various applications, including the development of electrochemical biosensors for blood sugar detection. These biosensors integrate the selectivity and sensitivity inherent in biosensing with the rapid response and real-time monitoring capabilities of electrochemical methods. Capable of detecting and analyzing diverse biomolecules, electrochemical biosensors are instrumental in healthcare, environmental studies, and the food industry. Specifically, in diabetes management, they play a vital role in continuously monitoring blood glucose levels, thereby aiding in accurate insulin administration [15,20].

Amperometry, a critical technology in blood glucose measurement, is central to Continuous Glucose Monitoring (CGM) systems [18,19]. It functions by measuring glucose concentration through the observation of electrical current changes. This technique is based on the principle that glucose, when reacting with specific reagents, causes variations in electrical current. There's a proportional relationship between glucose levels and the electric current: fluctuations in glucose concentration led to corresponding changes in current. This mechanism facilitates ongoing, real-time monitoring of blood glucose, reducing the necessity for regular blood sampling. Amperometry thus offers a more efficient and logical approach to managing blood sugar levels.

Electrochemical glucose sensors work by using an enzyme called glucose oxidase (GOx) to catalyze the oxidation of glucose [13]. The electrons generated by this enzymatic activity are transferred to the sensor's electrode surface. Electrodes are usually covered with a conductive substance and are used to measure the electric current produced by the transfer of electrons. The amount of current generated is inversely proportional to the glucose concentration of the sample. As a result, the current response increases with increasing glucose concentration. The technical accuracy of a blood glucose meter is related to how well the measurement provided by the meter matches the actual or reference blood glucose value [9]. It measures how accurately and consistently the glucose meter reads blood glucose levels. The technical accuracy of blood glucose meters is routinely evaluated through performance evaluation studies. In these studies, blood glucose meter readings are compared to readings from highly reliable laboratory analyzers or reference technologies. Reference methods may use venous blood samples examined by a central laboratory glucose analyzer or by clinical laboratory techniques such as spectrophotometry [15].

Two main metrics are often used to indicate the accuracy of a blood glucose meter:

1: Mean Absolute Relative Difference (MARD): MARD is the average percentage difference between a blood glucose meter measurement and a reference method measurement. Lower MARD numbers indicate greater accuracy [20].

2: Consensus Error Grid Analysis (EGA): EGA is a visual representation used to evaluate how accurately a meter affects patient health. It divides the classification areas of blood glucose meter results according to their clinical significance. There is a difference between clinically correct (does not affect treatment decisions) and clinically significant (may affect treatment decisions) [19].

The International Organization for Standardization (ISO) and other regulatory organizations provide standards and guidance for evaluating the technical accuracy of blood glucose meters. Manufacturers are often required to prove the accuracy of their blood glucose meters before gaining regulatory approval for medical use. Different blood glucose meters may have varying degrees of accuracy, and improvements in technology continue to make these devices more accurate over time. Technical accuracy is an important factor to consider when choosing a blood glucose meter, especially if accurate blood glucose monitoring is necessary for successful diabetes control [18]. The electrochemical glucose sensor allows us to monitor blood sugar very well, which allows us to treat diabetes more efficiently and accurately [20]. The integration of electrochemical technologies in diabetes management has marked a new era in patient care. These advancements not only offer improved accuracy and convenience but also pave the way for further innovations in the field. As research continues to evolve, it is anticipated that electrochemistry will play an increasingly significant role in diabetes treatment, potentially leading to more personalized and effective management strategies for this chronic condition [9].

4. Classification and distribution of medical equipment

Electrochemistry has not only revolutionized the monitoring and treatment of diabetes but also carved out a significant niche in the broader landscape of medical devices. Electrochemical devices, particularly those used in diabetes care like Continuous Glucose Monitoring (CGM) systems and advanced insulin pumps, fit within a unique category of medical technology [19]. These devices embody a synergy of biochemical sensitivity and electrical precision, setting them apart in terms of functionality and complexity. Medical equipment is very diverse and is an essential part of the treatment of diabetes. What we use most is continuous blood glucose monitoring, which is a type of point-of-care testing equipment. Medical devices have complex classifications and strict issuance standards. In terms of size and form, medical devices can be broadly divided into Centralized medical devices and decentralized medical devices [21].

Centralized medical devices and decentralized medical devices refer to two different models of medical device deployment and data management. Centralized medical devices are devices that are connected to a centralized system through a network, which is a multi-faceted medical device that can help achieve efficient monitoring, management, and maintenance. Most of the centralized medical devices are used by hospitals, clinics and other large medical institutions, basically as tools for diagnosis, monitoring and treatment [10]. Within the framework of medical device classification, electrochemical devices used in diabetes management are often categorized based on their risk level and complexity. Given their critical role in patient care and their advanced technological features, these devices are typically classified as moderate to high-risk, aligning with either Class 2 or Class 3 in the FDA's regulatory scheme [17]. This classification is reflective of their integral role in maintaining crucial health parameters and the need for stringent regulatory oversight to ensure safety and efficacy.

Decentralized medical devices, utilizing blockchain or distributed ledger technology (DLT), offer enhanced security and interoperability. These devices operate independently, without reliance on a central system or network, contrasting with traditional centralized medical devices [19]. Key advantages include secure data storage, as patient data on a distributed ledger is more secure and less vulnerable to hacking or unauthorized access [12]. Among these, Point-of-Care Testing (POCT) devices stand out. They are portable, easy-to-use diagnostic tools providing quick results at or near the patient's site, eliminating dependence on centralized labs. Ideal for use in various settings, from bedside to remote locations, POCT devices enable healthcare professionals to make prompt, informed decisions about patient care. This subset of decentralized medical devices brings benefits like enhanced speed, convenience, and improved patient care, representing a significant advancement in medical technology [14].

Continuous Glucose Monitoring (CGM) systems are invaluable in diabetes management, providing instantaneous updates on glucose levels. These systems are composed of three main elements: a sensor, a transmitter, and a receiver or smartphone application. The sensor, a diminutive electrode, is inserted under the skin, typically in the abdomen or arm area, to gauge glucose levels in the interstitial fluid. It continuously sends these glucose measurements to the transmitter, a small device linked to the sensor. The transmitter then wirelessly forwards this information to a receiver or a smartphone app, allowing individuals to track their glucose levels in real-time. CGM systems are often equipped with alarms and notifications to alert users of high or low glucose readings, which is crucial for effective diabetes management [19]. By providing detailed data on glucose patterns and changes, CGM systems assist users in making well-informed choices regarding their diet, medication, and insulin dosing, thereby aiding in maintaining optimal glycemic control.

In the United States, the Food and Drug Administration (FDA) stringently regulates the distribution of medical devices [10]. This federal agency oversees the safety and efficacy of food, drugs, medical devices, cosmetics, biological products, and radioactive items. Its primary objective is to protect public health and safety while fostering scientific innovation. For medical devices to be developed and applied, FDA approval is crucial. The agency assesses a device's safety and effectiveness before it can be marketed. Beyond initial evaluation, the FDA sets quality standards, performs post-market

monitoring, and inspects manufacturers for compliance with legal mandates. Medical devices are categorized and regulated based on factors like risk level and intended use, ensuring a high standard of public health and safety [9].

Medical devices are classified by the FDA according to their risk level, which might change based on scientific data. There are three classes:

Class 1: Least Risk, Subject to general controls ensuring safety and effectiveness, and includes good manufacturing practices, reporting adverse events, registration, and recordkeeping.

Class 2: Moderate Risk, Subject to general controls and special controls, and special controls involve labeling, performance standards, and testing requirements.

Class 3: High Risk, requires premarket approval, and applies to life-sustaining or implanted devices with potential high risk. It must prove safety and effectiveness and is also subject to general controls.

Different Classes have different control measures:

- 510(k): Requires proof of substantial equivalence to legally marketed devices without PMA. Devices with the same intended use and technology as pre-amendment devices or reclassified ones are considered substantially equivalent.

- Premarket Approval (PMA): Rigorous review for Class III devices or non-substantially equivalent Class I/II devices. Requires scientific evidence of benefits outweighing risks and significant help for the target population.

Strict control of medical equipment ensures that each device is properly tested and evaluated before being put into use, thus maximizing patient safety. As technology advances, new medical devices and treatments are constantly emerging. Strict classification and control of these new technologies can ensure that their introduction is orderly and safe.

5. Conclusion

Diabetes, especially type 2 diabetes, is becoming increasingly common worldwide. Multiple factors have contributed to the increase in the incidence of diabetes, including changes in lifestyle (long periods of sitting, lack of exercise, unhealthy eating habits, etc. are all associated with an increased risk of type 2 diabetes), the obesity epidemic, and the aging of the population [2,4,5]. Therefore, in such a social situation, the management and treatment of diabetes are particularly important.

Managing blood sugar is vital for people with diabetes, directly affecting their health and quality of life. Stable blood sugar levels help avert acute risks like severe hyperglycemia or hypoglycemia and significantly lower the likelihood of chronic complications such as cardiovascular disease, kidney and nerve damage, and vision loss [1,6]. Furthermore, consistent blood sugar control enhances daily energy and mood, thereby improving overall well-being. In the long run, effective management not only prolongs life but also reduces the financial burden associated with diabetes-related complications [8,20].

The landscape of diabetes treatment is evolving towards personalized medicine. Advances in genomics and biomarker research are paving the way for more customized treatments, tailored to each patient's genetic profile and specific disease attributes [16]. Innovative sensor technologies, including advanced Continuous Glucose Monitoring (CGM) systems, are set to provide more accurate, real-time glucose data. These advancements promise not only enhanced monitoring comfort but also immediate feedback for better disease management.

The future of diabetes care is intrinsically tied to technological progress and individualized treatment strategies [17]. The goal is to not just control the disease but to significantly improve the life quality of those affected. With ongoing advancements in technology and treatment methods, there's a strong hope for a future where diabetes management becomes more effective, less invasive, and uniquely suited to individual needs.

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