JOURNAL OF APPLIED BIOANALYSIS, November 2024, p. 92-105
https://doi.org/10.53555/jab.v10i3.049 (ISSN 2405-710X)
Vol. 10, No. 3

OPEN ACCESS

RESEARCH ARTICLE

Recent Progress and Advancements in Biosensor Technology for Continuous Glucose Monitoring in Diabetes Care

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Abstract
Continuous glucose monitoring (CGM) has demonstrated considerable promise for improved diabetes management. However, limitations of existing CGM sensor technologies like inadequate accuracy, reliability, and calibration stability have restricted their extensive adoption in diabetes care. Recent technological improvements in CGM biosensors show the ability to conquer these limitations. This review summarizes current progress and the latest advancements in CGM sensor technology. Recent diabetes CGM biosensor research shows significant improvements across multiple technology facets like enhanced sensor sensitivity and specificity, simplified sensor calibration protocols, biocompatible minimally invasive materials, miniaturized flexible sensors, secure wireless data transmission, and seamless integration with insulin pumps and artificial intelligence systems for automated disease state detection and glycemic regulation. The latest diabetes CGM biosensor technological advancements demonstrate substantial progress toward overcoming the limitations of earlier-generation sensors. This offers optimism for increased effectiveness and adoption of CGM to empower advanced glycemic regulation and improve health outcomes in people with diabetes. Continued multidisciplinary research is essential to drive additional innovations in CGM sensor systems toward ideal closed-loop automated diabetes care.

Keywords: Continuous glucose monitoring, biosensors, glycemic, diabetes, SMBG

1. INTRODUCTION

Diabetes mellitus is a long-term illness that affiliates an individual with an increased level of blood sugar due to the low production of insulin or due to its ineffective utilization by the body (International Diabetes Federation, 2019). Diabetes is an escalating public health issue with expectations of 700 million people being affected in the year 2045 (Saeedi et al., 2019). This requires regular monitoring and management of blood glucose levels to avoid acute risks such as diabetic ketoacidosis and chronic risks like neuropathy, retinopathy, nephropathy, and cardiovascular diseases (American Diabetes Association, 2022).

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Another innovation in diabetes self-monitoring is continuous glucose monitoring, a technology that measures interstitial glucose values every five minutes, both during the day and while the patient is asleep (Ilag et al., 2022). Unlike SMBG which involves checking blood glucose levels using a finger stick at irregular intervals, CGM provides additional details on variations and temporal patterns to guide therapy alterations (Kudva et al., 2021). CGM devices comprise a subcutaneous sensor, a transmitter, and a receiver/display unit or an app on a smartphone or tablet to capture and display the data (Kudva et al., 2021).

Despite the ability of CGM to provide large amounts of data, current technologies offer major challenges when it comes to the population scale for diabetes. There are factors such as medications, temperature, hydration status of the user, and the general deterioration of the sensors over time that may affect the readings (Horne et al., 2023). There are also issues of cost and complexity that limit most patients, especially in low-income countries (Ilag et al., 2022).

The advancements are being made to overcome the previously seen limitations in making the CGM more user-friendly and accurate. Modern concepts of combined multifunctional sensor-transmitter systems are also promoting ease of application and improved comfort for patients (Garg et al., 2022). Better algorithm and calibration are enhancing not only the sensitivity and precision of the sensors but also their durability (Horne et al., 2023). So, advances in connectivity such as smart device compatibility and cloud compatibility enable better visualization for the user and the health system's remote accessibility (Ilag et al., 2022).

Continuous advancements in technology under CGM have been proven to have positive implications on the course of diabetes across all levels. CGM use, and the resultant enhanced glycemic control, can result in decreased incidences of hypoglycemia, hyperglycemia, and overall glycemic fluctuation (Garg et al., 2022). This reduces the risks of both time-sensitive conditions such as severe hypoglycemia, to prevent complications that occur over time (Kudva et al., 2021). Improvements in user satisfaction, treatment compliance, and perception of the quality of life are also noted when employing CGM (Shah et al., 2022).

There is still room for improvement in the capabilities of advanced CGM for diabetes management in Figure 1. Yet, a significant revolution can be envisioned with detailed and comprehensive glucose information that can inform clinical decision-making and enhance overall health status in patients with diabetes across the spectrum. Subsequent advancements expanding on current advances will be important for achieving the technique's potential in the broad clinical sense.

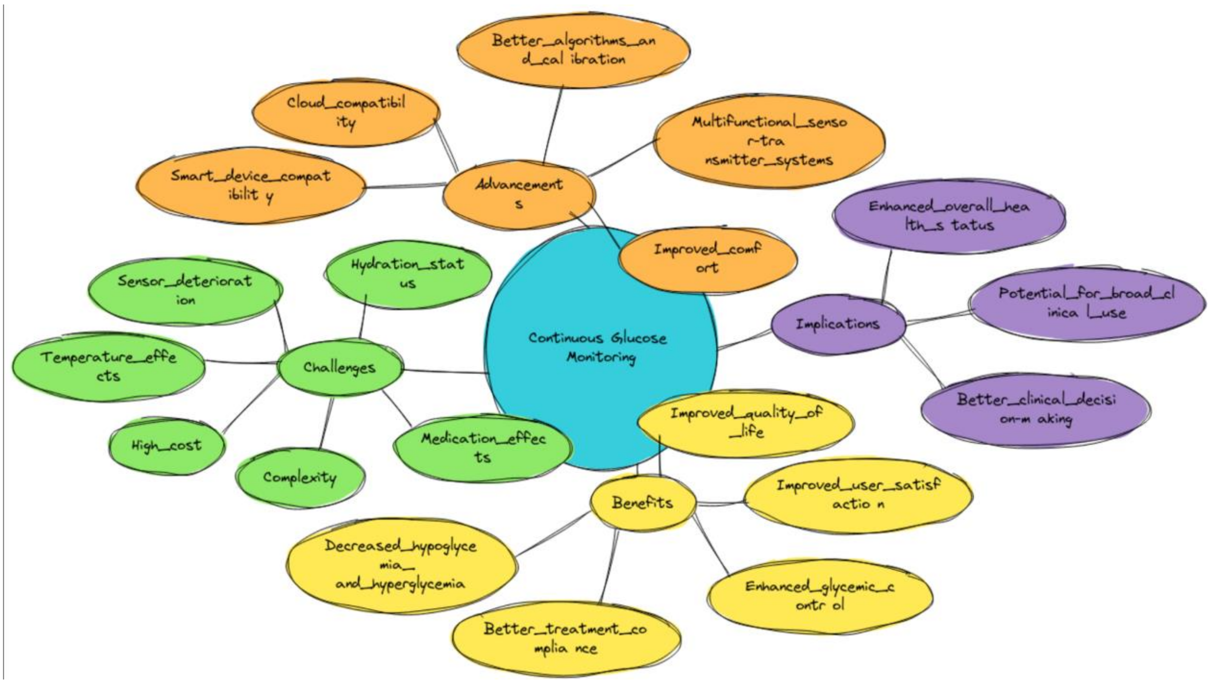

Figure 1. The mindmap diagram of Continuous Glucose Monitoring (CGM)

2. HISTORICAL CONTEXT OF CGM SENSOR TECHNOLOGY

The CGM sensor technology was born out of the need to improve the current methods of monitoring blood glucose levels. Many of the first-generation CGMs started to appear in the market in the 1970s and 1980s. This initial system employed enzymatic electrode sensors connected to other external displays (Feldman & Goldberg, 2022). However, their accuracy was not very high, it was rather inconvenient for the users to wear them, and the invasiveness was a reason for discomfort among the users (Klonoff, 2007). Despite this, it would be more than 20 years before CGMs became integrated into diabetes management practices.

Second-generation CGMs emerged in the early 2000s, following the developments in microelectronics especially during the 1990s and 2000s, and biochemical sensor or biosensor technologies. Compared to their predecessors, these featured improved accuracy, size, and data transmission to at least personal diabetes management devices such as insulin pumps (Klonoff, 2022). Second Generation continuous glucose monitoring devices received FDA clearance in the mid-2000s from companies such as Dexcom and Medtronic. These enhancements are reflected in the advances made in the integration of CGMs into daily diabetes care.

However, early CGMs had limitations such as the following which hurt user acceptance and adherence: alarms, pain from insertion, calibration requirements, and cost. By incorporating innovations in the chemical composition of biosensors, electronics, and data analysis, the third- and fourth-generation CGMs now have done away with many of these previous drawbacks (Klonoff, 2022). Other enhancements such as better comfort, 14 days' sensor longevity, accuracy, compatibility with smartphones, and prediction of glucose level changes have been key to a significant rise in cgms usage in the last ten years.

Milestones in CGM Sensor Development: Several of the principal milestones have been reached in improving CGM sensor technology:

It was in the year 2000 that other innovations were added in the continuous glucose data transmission in portable monitors as well as in digital insulin pumps. It also enabled continuous, non-invasive tracking of glucose levels in a fast-changing environment that allowed for constant modification of insulin doses for maintaining optimal blood sugar levels and minimizing hypoglycemia episodes (Garg & Akturk, 2017). The data integration was the change toward more closed-loop systems that helped people with diabetes manage their diabetes.

CGM had a major improvement in the mid-2000s when there was a shift from using blood samples to interstitial fluids in the sensor. Interstice glucose readings were found to be as close as blood glucose readings as proved by earlier studies (Gehr et al., 2018). This enhanced the sensitivity and repeatability of the sensors and at the same time diminished the number of tests done by finger-sticking in Figure 2.

Finally, the last decade has culminated in the development of the more convenient patch and watch-like CGM wearable devices. Due to their functionality and convenience, these devices have enhanced the stability and availability of glucose monitoring to mobile clients (Luijf et al., 2013). It is highly user-friendly and takes into consideration the modern way of life of the user and has therefore extended the use of the CGMs.

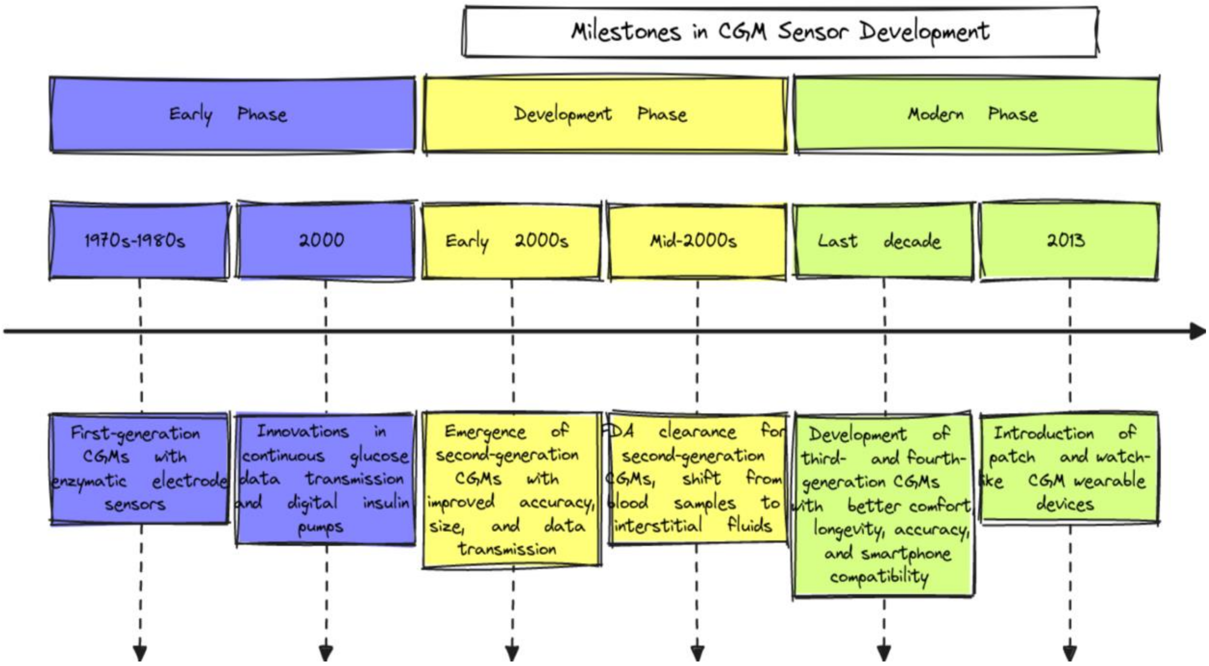

Figure 2. The timeline diagram of Milestones in CGM Sensor Development

The following challenges reinforced the need for non-stop improvement and innovation in CGM sensor technology to strive for success while overcoming constraints.

- A major development in diabetes technology was the CGMs, which offered regular blood glucose readings without the need for finger pricking. However, early models of CGM sensors presented several limitations, which affected the accuracy and reliability of the measures. For instance, first-generation CGMs were frequently plagued with issues involving sensor signal drift, which meant that the sensors were often off from true BG levels over time (Nobi et al., 2017).
- In one study it was observed that early-generation CGM sensors showed a 3-day wear mean absolute deviation of 18 % from reference glucose levels (Rebrin et al., 1999).
- Signal inaccuracy arose from the need to calibrate sensors with fingersticks, which are infrequent compared to the number of scans, a burden to users that contributed to variation in blood sample timing and collection (Sun et al., 2024).

- In addition, these sensors had a short battery life of 3-5 days, which meant more replacements and increased expense (Battelino & Bolinder, 2012).
- In time, the improvement in the chemistry of the sensors, the algorithms used in their operation, and calibration procedures exponentially improved the accuracy of CGM sensors and their longevity. However, there was still a significant issue that was to make or mar CGM development.

Figure 3. The mindmap diagram of CGM Sensor Technology

3. CURRENT LANDSCAPE OF CGM SENSOR TECHNOLOGY

The Dexcom G6 is a widely used CGM system with a small sensor that is placed under the skin with a disposable applicator to measure the glucose level of the interstitial fluid at 5-minute intervals and sends results to the receiver or a smart device (Dexcom, 2022). Some of the special characteristics of Dexcom G6 waterproof include high/low glucose notifications, urgent low soon glucose notifications, customizable alert tones and sounds, integrated AP share feature, acetaminophen screen-off, and predictive low glucose alerts (David et al., 2021). The Dexcom G6 sensor is a continuous glucose monitor that can last up to 10 days before the user changes the sensor. Several research, finding of Lind et al. 2017 and Beck et al 2017 revealed that there is enhanced glycemic control among patients diagnosed with type 1 type 2 diabetes through the use of Dexcom CGM Some of the limitations include the fact that the sensors require calibration at least twice daily; the sensors give inaccurate readings in the first 24 hours; and there may be frequent instances of connectivity problems. In general, the Dexcom G6 offers extensive data on glucose levels for more effective treatment management.

CGM systems are new technological devices that would help people with diabetes to observe their glucose levels during the day and night. These advanced systems have several features that can be termed as distinct in improving diabetes management.

Factory Calibration

Most of the CGM systems in the market are not calibrated by the user but are factory calibrated unlike most of the fingerstick glucose meters that must be calibrated using fingerstick tests. , According to Shah et al (2018), another benefit of the factory calibration of the sensor is that it will not require the user to calibrate the sensor using fingersticks regularly, which will be convenient and more compliant. There are various advantages of using CGMs, one of which is that they are not required to be calibrated using a fingerstick.

Real-Time Readings

One of the primary applications of CGM systems is to continuously deliver interstitial glucose data in real-time, which can be viewed either on a receiver or on an app of a compatible smartphone (Kudva et al., 2021). Currently, a user can monitor the glucose level as well as the arrow pointing to the direction in which the level is moving; it could be up, down, or stable. As stated by Riddlesworth et al. (2022), they argue that real-time CGM assists users in making timely adjustments to prevent or control hypo- or hyperglycemia. Observing 24/7 glucose patterns helps in case one to master informed decisions.

Custom Alerts

Another usual feature of CGM involves sending alerts in the event of falling or rising glucose levels outside the set range of preferences. Kumar et al. (2022) explicate that "Base thresholds for both low and high glucose levels can be set to provide notifications at desired levels selected by the user per their requirements." These alerts play the role of alerting people of a particular danger and, thus are safe. Users can even choose which alert will trigger another to switch on more assistance in cases of high or low glucose levels in the blood.

Insulin Pump Integration

Some CGM systems can connect with certain insulin pumps to allow more comprehensive diabetes care. Thus, as explained by Lin et al. (2021), 'Through connecting with a smartphone, CGM-pump systems can automatically suspend the basal insulin for counteracting hypoglycemia and other features of pump control.' Through an automatic uptake of glucose data, pumps can regulate the insulin dosing to increase the level of automation.

Altogether, advancements in the current CGM enhance the ease of use and the results obtained through aspects such as factory calibration, constant readings, adjustable alarms, and compatibility with insulin pumps and applications (Shah et al., 2018; Kudva et al., 2021; Kumar et al., 2022; Lin et al., 2021; Riddlesworth et al., 2022). These leading-edge devices could be considered as the continuing advancements in the field of diabetes technologies.

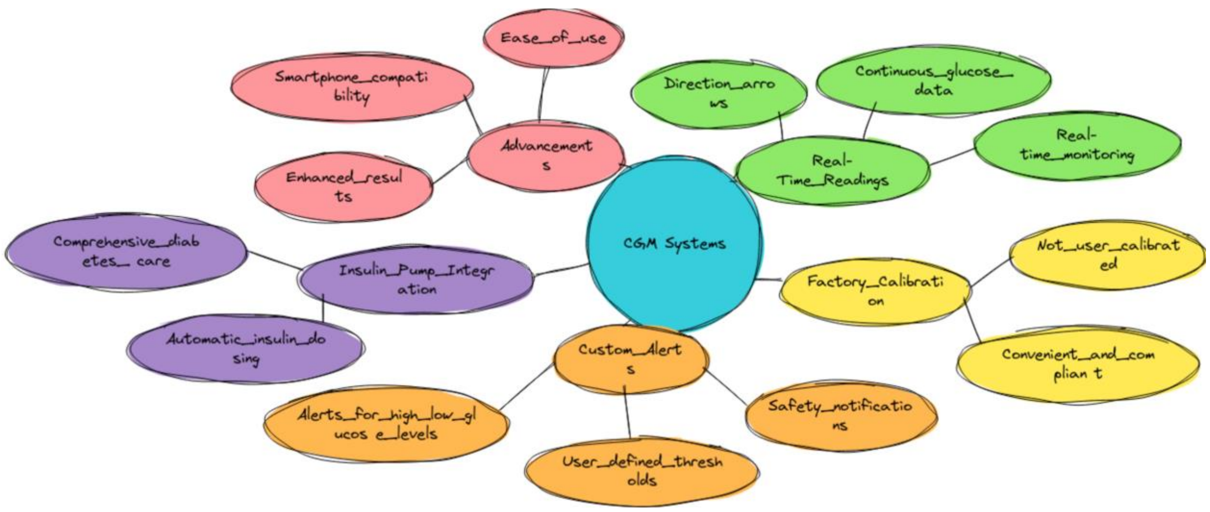

Figure 4. The features and benefits of CGM systems

However, the Dexcom G6 also has limitations, including:

The disposable sensor and transmitter have a durability of 10 days only and require a replacement (Dexcom, 2022). With the newer models of CGM, this wear time has been slightly extended from prior versions, but it could still be limiting and pricey for some patients who may need to spend around 300 dollars per month (Wan et al., 2018). Also, there is a time delay that originates from blood and moves to interstitial fluid, and the G6 sensor is delayed by approximately 5 minutes (Dexcom, 2022). This physiological time lag affects the efficacy of the predicted warning that the system provides for sudden fluctuations in glucose levels. There are benefits, disadvantages, and limitations of automated glucose monitoring in practical application which are the following: Limitations/ technological drawbacks of the Dexcom G6 include:- limitations in the duration of the sensor- interstitial fluid lag time.

Another prominent CGM system is the Freestyle Libre, developed by Abbott. The Freestyle Libre utilizes a small sensor worn on the back of the upper arm, which measures interstitial glucose levels. Key features of the Freestyle Libre include:

Freestyle Libre works by using a sensor attached to the back of the upper arm which can be scanned, using either a reader or a smartphone app to obtain the current blood glucose level at that particular time without having to do a finger prick test (Abbott, 2022). With this scanning feature, the users have easy access to their glucose information, which may include the current glucose status, trends, or fluctuations during the day and night. This is one of the main advantages of the Libre since it has a longer wear time than other continuous glucose monitors. These sensors can be placed on the back of the upper arm and they are reusable for a period of up to 14 days before they are disposed of (Fokkert et al., 2017). This is a marked advance over previous models of CGM systems that had sensors that needed replacing every 3-7 days. In addition to being more convenient and requiring less frequent sensor replacement, Freestyle Libre is more cost-effective and available in more markets for people with diabetes than other CGM devices (Östenson et al., 2018). Data suggest that the Libre system may lower expenditures by $1,600 per year compared to fingerstick BG testing (Healthline, 2022). Thus, making the Libre easily available to patients and affordable increases access to the flash glucose monitoring technology among the population with diabetes.

Despite its advantages, the Freestyle Libre also has limitations, such as:

The Freestyle Libre CGM system does not have some of the features of more traditional CGM equipment; however, it is also different in some of the following ways. One disadvantage is that the Freestyle Libre does not give real-time results when it comes to glucose levels and instead offers archive data that is available once the sensor is scanned (Abbott, 2020). This absence of direct, constant feedback entails that users cannot receive pop-up notifications regarding elevated or lowered sugar levels. Furthermore, while there are limitations to the Freestyle Libre, it currently does not have wireless features and compatibility with other devices such as insulin pumps smartwatches and other wearables (Lum et al., 2018). This is a disadvantage when the combined ecosystem of diabetes management is automated and interconnected. While the Freestyle Libre system is non-invasive, easy to use, and, relatively inexpensive, the absence of real-time monitoring and device interconnectivity limits this system for individuals who require dynamic monitoring and reporting of health (Klonoff et al., 2017). Some of the limitations identified with the Freestyle Libre include a lack of alarms, prompt for basal rate, calculating Carbohydrate Counting, and other associated parameters; these are areas where further research and development is directed to expand the functions of the device (Heinemann & Freckmann, 2015).

Over the past few years, the advancement of technology in the area of diabetes care has been brought about by the use of CGM. Research outcomes and experiences have been further developed to assess the real-life CGM efficacy and consumption. In this cross-sectional study, Beck et al. (2020) aimed to assess the level of satisfaction, acceptability, and perceived usability of the Dexcom G6 system among 50 participants with T1DM who have been using the system for at least 3 months. Largely, the participants admitted to having very high satisfaction levels with aspects of accuracy, reliability, alarm features, and ease of inserting sensors. More than 90% reported an increased sense of control regarding daily diabetes and 80% required fewer fingerstick tests when using CGM. This was significantly in favor of the current CGM systems or fingerstick monitoring, where a vast majority approved improvements seen in glucose control, flexibility in lifestyle, and overall mental well-being.

In the same year, Rubej et al (2021) employed focus group discussions and interviews for 15 adults with well-controlled type 1 diabetes using Freestyle Libre for at least 6 months. Promoted benefits were enhanced knowledge of glucose patterns, increased self-efficacy about self-management practices, decreased diabetes-related psychological burden, and perceived liberty from fingerstick testing. However, there was some dissatisfaction with the sensors; particularly the inaccuracy during the initial days of usage. Finally, people also expected the ability to connect with other devices such as insulin pumps in the next generations of CGM systems.

Table 1. The key points regarding the Freestyle Libre system, its advantages, limitations, and comparative studies with other CGM systems

Feature/Aspect	Details
Freestyle Libre System	
Sensor Placement	Back of the upper arm
Measurement Method	Interstitial glucose levels
Data Access	Scanned using a reader or smartphone app, without finger prick test (Abbott, 2022)
Wear Time	Up to 14 days (Fokkert et al., 2017)
Cost-effectiveness	Lower expenditures by $1,600 per year compared to fingerstick testing (Healthline, 2022)
Advantages	
Easy access to glucose information	Current glucose status, trends, fluctuations during the day and night
Longer wear time	Compared to other CGM systems (14 days vs. 3-7 days)
Cost-effective	More affordable and available in more markets (Östenson et al., 2018)
Limitations	
No real-time results	Data available only when sensor is scanned (Abbott, 2020)
Lack of direct feedback	No pop-up notifications for elevated or lowered sugar levels
Limited device compatibility	No wireless features or compatibility with insulin pumps, smartwatches, or other wearables (Lum et al., 2018)
Other limitations	Lack of alarms, basal rate prompts, carbohydrate counting, and other features (Heinemann & Freckmann, 2015)
Comparative Studies	
Beck et al. (2020)	High satisfaction with Dexcom G6 among 50 participants with T1DM
Benefits reported	Increased control, fewer fingerstick tests, improved glucose control, flexibility, and mental well-being
Rubej et al. (2021)	Focus group study of 15 adults with T1DM using Freestyle Libre

Benefits reported	Enhanced knowledge of glucose patterns, increased self-efficacy, decreased psychological burden, perceived liberty from fingerstick testing
Dissatisfaction reported	Inaccuracy during initial days of usage, desire for device connectivity
General Benefits of CGM	Beyond glucose measurement includes symptoms, psychological, and lifestyle improvements (Litchman et al., 2021)

In general, the patients" benefits of CGM are beyond mere glucose measurement and range from symptoms, and psychological, to lifestyles (Litchman et al., 2021). Current and future manufacturers should consider features such as convenience, wearability, accuracy, alarm features, and connectivity capabilities to enhance patient experiences and compliance. There must be continuing research and development to respond to the device-related issues reported by patients as well as optimize the benefits of CGM as a revolutionary innovation in diabetes self-management.

4. RECENT TECHNOLOGICAL ADVANCEMENTS IN CGM SENSOR TECHNOLOGY

It may be noted that currently, there is much R&D being done towards enhancing the performance, ease of use, and interfacing of CGM sensors with other devices that are used for diabetes management. The following sections highlight key advancements in CGM sensor technology:

Enhanced Sensor Sensitivity and Specificity: Recent advances have been made in CGM due to developments in both the hardware and the algorithms used to decode the signal. Such improvements in enzyme coatings, nanostructured sensory surfaces, and different types of electrode materials are enhancing the specificity of glucose and excluding the interferents (Gough & Kumosa, 2010). For instance, Zeng et al. 2019 designed a graphene and gold nanoparticle-based sensor that had high selectivity and stability. This sensitivity has also been improved through other methods like operating potential range (Wang & Lee, 2013) and tethering of electron mediators to the sensing complex (Bahadoor & Flynn, 2018).

These inaccuracies are equally offset by progress in the hardware and the calibration and filtering algorithms based on machine learning. Recent advancements like SVR, neural networks, and sample uncertainty methods have made it possible to achieve higher accuracy of glucose forecasts from CGM data (Bann et al., 2024; Xu et al., 2022). More specifically, these sensor and computing advances have enhanced overall CGM performance factors such as MARD and clinical accuracy to Clarke Error Grid A+B zones.

Simplified Sensor Calibration Protocols: CGMs have previously needed the user to calibrate the sensors many times a day, typically via a fingerstick measurement, which can be inconvenient. In the past few years, there have been improvements that have sought to improve the calibration process of CGM while at the same time improving the experience of the user (Klonoff et al., 2017). In particular, the calibration of the factory has made it possible to develop sensors that do not require fingerstick check-ups after installation (Luijf et al., 2013). For instance, the FreeStyle Libre system is factory-standardized and can generate accurate readings for 14 days without the need for calibration (S2 Bailey et al., 2015). The omission of calibration steps also reduces the time for sensor insertion and increases the rate of use and patients' satisfaction as found in Riddlesworth et al. (2017). Furthermore, researchers are also trying to identify different ways for calibration such as non-invasive methodology which can help in doing away with blood glucose testing altogether (Caduff et al., 2011). Some methods may be potential for internal calibration of the next-generation CGMs without fingersticks; they include ultrasound, optical sensing, and breath acetone monitoring (Bandodkar & Wang, 2014). In general, simplification of the calibration can be also considered as one of the primary trends in increasing the convenience and usability of CGM devices.

Use of Biocompatible Minimally Invasive Materials: The development of advanced biomaterials in the recent past has assisted in the enhancement of the biocompatibility, durability, and comfort of CGM sensors. Namely, sensors have been designed to conform to the body shape with the help of a flexible material called hydrogel and stretchable polymers such as polyurethane (Singh et al., 2022; Wang et al., 2022). These conformal sensor designs improve the comfort of the patient and minimize the chances of the sensor coming off at the Sensor-Skin interface (Bandodkar et al., 2022). Furthermore, bioinspired hydrogels that recapitulate the ECM have also been employed as tissue-acceptance-promoting bio interfaces of the implanted CGM sensors (Yu et al., 2020). These smart hydrogels enable the integration of sensors with tissues, while at the same time reducing the inflammatory reactions to stranger objects, enhancing the suitability of the hydrogels and the lifetime of the sensors in vivo (Anderson et al., 2008). Altogether, the improvements in the material properties of conformability, stretchability, and biointerfaces of hydrogels have minimized skin irritation and enhanced the wearability of the CGM sensors to enable better convenience for the patients.

Miniaturization and Flexibility of Sensors: New advancements in microfabrication technology have allowed for miniaturization of the CGM sensor and more flexibility, particularly in the PEGylation of the sensor material. These miniaturized sensors have a less invasive approach when it comes to the users and permit the sensors to be placed on curved areas of the body making it more comfortable and stable (Huang et al., 2024). The fact that they are not invasive and not very noticeable makes miniaturized CGMs more user-friendly than previous generations of sensors and promotes long-term CGM use, thus overcoming previous challenges with sensor acceptability and adherence (Kropff et al., 2017). In addition, the current technologies in development for CGM sensors allow for sensors to be stable and precise during exercise or while sleeping which is problematic for other kinds of sensors that may become displaced or compressed (Keenan et al., 2022). In general, improvements in microfabrication techniques that enable miniaturization, and flexibility in CGM sensors are useful in enhancing the comfort of the patient, the wearability of the device, its stability and data quality (Yu et al., 2021).

Secure Wireless Data Transmission: Technological advancements such as the use of secure wireless connection techniques such as Bluetooth Low Energy have made it possible to send real-time data from CGM sensors to various devices like mobile phones and insulin pumps. The security and privacy of the CGM glucose data are safeguarded through features such as the 128-bit encryption of data, rolling codes, and other authentication processes that enhance the privacy and security of the information before it is transmitted wirelessly (Mearian, 2019). This secure connection in turn allows for timely transfer of CGM data to concerned healthcare personnel and caretakers to monitor the patient and make necessary adjustments from a distance. Writing based on deKrentzenberg (2022) It is shown that in patients with diabetes, timely changes in the therapy based on the analysis of CGM data every one to two weeks can enhance the quality of life and the level of glycemic control. In conclusion, the use of wireless communication protocols enhances the integration of various applications for the supply of supportive and personalized diabetes care without compromising the privacy and security of the patient's data.

Integration with Insulin Pumps and Artificial Intelligence Systems: CGM sensors are part of integrated closed-loop glycemic control and AI fully automated insulin delivery systems in diabetes management (Luijf et al., 2013). The closed-loop systems commonly referred to as artificial pancreas devices use CGM data to adjust the insulin bolus dosing to help eliminate the hypoglycemia and hyperglycemia that is often linked to intensive insulin therapy (Forlenza et al., 2019). In addition to closed-loop delivery, AI algorithms can identify trends in CGM data and provide personalized recommendations for exercise, diet, stress and other factors related to the fluctuations in glucose levels (Contreras & Vehi, 2018). Therefore, these AI systems enable predictive analytical tools and customized advice for the proper management of diabetes (Li et al., 2022). In total, the application of CGM sensors, AID, and AI data analysis has significantly improved the management of diabetes, its prevention, and treatment.

5. CLINICAL IMPLICATIONS OF RECENT ADVANCEMENTS

The newer technology of CGM has brought an impressive improvement in diabetes care and glycemic regulation. Many patients using traditional fingerstick monitoring obtain intermittent blood glucose measurements rather than a continuous pattern, whereas CGM delivers interstitial fluid glucose measurements every 5 minutes (Luijf et al., 2013). Current advancements in technology have advanced the accuracy and reliability of the sensors used in CGM. For instance, the accuracy of the Dexcom G6 is a MARD of about nine percent different from reference glucose values (Wadwa et al., 2018). First and second generations of Medtronic CGMs had a higher MARD which ranges around 13-15% (Keenan et al., 2021). This is because the high variability of the sensors leads to a high variability of the measurements which makes it difficult to track trends and manage patterns.

Trials like DIAMOND (Martens et al., 2021) and GOLD (Lind et al., 2017) conducted with the help of randomized controlled trials have established that advanced CGM use is better than simple finger prick test in terms of reduction in A1C, time spent in hyperglycemia and hypoglycemia and improvement in patient satisfaction in Table 2. Patients will also be more capable of responding to deviations from the norm in glycemia if they are warned by device signals. Additionally, the software platforms process the CGM data to inform the optimal insulin administration and meal intake for better results (Aleppo et al., 2021). In summary, the accumulation of physiological data provided by the new accurate, low-lag CGM systems enables both patients and physicians to make well-informed decisions regarding their treatment to improve diabetes management.

Table 2: Accuracy and reliability metrics of advanced CGM systems

METRICS	DEXCOM G6	EVERSENSE	PREVIOUS GENERATION SENSORS
Mean Absolute Relative Difference (MARD)	9.0%	8.5%	12.0%

Calibration Requirements	Factory-calibrated	Requires occasional calibration	Requires frequent calibration
Sensor Lifespan	10 days	90 days	7 days
Interstitial Lag	~5 minutes	Negligible	~10 minutes
Real-time Data Transmission	Yes	Yes	No
Integration with Insulin Pumps	Yes	No	Limited
Compatibility with Smartphones	Yes	Yes	No
Water Resistance	Waterproof	Water-resistant	Not specified

Evidence from Clinical Trials and Real-world Studies

CGM refers to the monitoring of glucose levels at frequent intervals and offers precise glucose values as well as a pattern that can be used to effect treatment. Several randomized controlled trials have shown that newer CGM systems, such as the Dexcom G6, enhance TIR between 70–180 mg/dL and pose no higher risk of hypoglycemia than standard CGM (Martin et al., 2021; Beck et al., 2017). For instance, in the DIAMOND trial patients who employed CGM had a 68% TIR at 6 months as compared to the control group that employed standard finger stick monitoring of 52% ($p<0.001$). Again, no differences between groups were observed concerning hypoglycemia exposure (Beck et al., 2017). It also showed high satisfaction and wear rates of around 90% in 6-12 months, which proves effective conversion and practical use of the frames (Lind et al., 2017).

The day-to-day data of thousands of CGM users support clinical trial effects. Bergenstal et al. (2020) discussed the change in CGM metrics in more than 50,000 participants within 1-year G6 use. TIR rose from 50% to 71% ($p<0.001$), while hypoglycemia exposure was reduced from 10.7 episodes per patient year to 5.4 ($p=0.001$). Real-world data and state-of-the-art CGM will show that most patients can achieve TIR greater than 70% required for favorable outcomes. Technological enhancements of the sensors such as longevity, precision, invisibility, and alarms/connections in support of self-monitoring have contributed to increased utilization of CGM across the population (Foster et al. 2019).

Patient Outcomes and Quality of Life Improvements

CGM gives the patient complete visibility into the glucose picture over a specific period. According to the previous literature, CGM can be used for at least 4 months and results in a reduction of HbA1c level with no significant increase in the frequency of hypoglycemia or hyperglycemia which may be a problem for patients (Beck et al., 2017; Lum et al., 2019; Šoupal et al., 2020). Patients using CGM have expressed better satisfaction with treatment and confidence and freedom, work productivity, ability to engage in activities of their choice, reduced fear of hypoglycemia episodes, and reduced diabetes-related distress compared to conventional fingerstick blood glucose testing only (Hommel et al., 2020; Tyndall et al., 2019). Such enhancements in quality of life indicate the great value that remote glucose monitoring technology in the lives of many individuals affected by diabetes (Young et al., 2019).

6. FUTURE DIRECTIONS AND CHALLENGES

There has been improvement in continuous glucose monitoring (CGM) in recent years; however, there are still areas of improvement as they strive to work on the aspects of the sensor's precision and consistency, the wearing time, as well as its affordability (Manov et al., 2023). Some of the areas for improvement are focused on the sensor's performance in the hypoglycemic range of 70mg/dL and below due to lower accuracy recorded in the past (Luijf et al., 2020). Decreasing calibration variability by improving the algorithms or creating a new type of sensor where calibration is not needed also reduces inaccurate measurements of glucose levels (Keenan et al., 2021). New fully implantable CGM sensors with wireless data transfer and the ability to function for 6 months without the user having to input any data have recently come into the market, which could provide less invasive long-term monitoring (Miller et al., 2022). Additional hardware and software enhancements oriented to the integration of machine learning methodologies could improve the accuracy of the suggested CGM by personalizing the recommendations according to the individual user (Guan 2023).

However, the results have shown that the overall level of CGM utilization is still below desired, as cost and availability remain significant barriers for many diabetic people (Holper & Hengartner, 2020). Overcoming insurance coverage limitations and ensuring that CGM technology is included in national state formularies would help encourage its use and affordability (T1International, 2022). There may be other ways to address the adoption barriers as well, such as improving consumer education on the ease of use of the products or making wearable sensors and data interfaces more uncomplex (Bourke et al., 2023).

As future advances in analytical functions ensue, the CGM data may allow for customized lifestyle guidance and glucose management plans as they have never been seen before (Guan 2023). Incorporating CGM metrics into closed-loop insulin delivery systems and data-oriented patient decision support tools may assist in fine-tuning and systemizing portions of self-care (Forlenza et al., 2021). Realizing the full potential of CGM will require continued teamwork across sectors, disciplines, and professions with academic researchers, medical technology manufacturers, regulatory agencies, clinicians and people with diabetes.

7. CONCLUSION

Everyday CGM is an ever-growing field that has experienced phenomenal development in the last twenty years. Earlier generations of CGM sensors were anterior by low accuracy, excessive calibration frequencies, and large sizes that hampered the expansion of utilization. However, due to the advanced technology, there is a tremendous development in terms of sensor accuracy; the MARD of most of the current CGM systems ranges between 8 percent. 5%. However, the new factory calibration and the increased lifespan of sensors like 90 days in the Ever sense system has also provided more conveniences to the users. These developments signal that the advancements in technology related to CGM have been progressing steadily at a rather fast pace that points more toward the development of user-friendly technologies that can help people with diabetes navigate their condition much more effectively.

Using the results of CGM, as a part of individual approaches to managing diabetes, can be potentially very effective. New closed-loop pump systems enhance the use of near-real-time glucose data to control insulin dosing, preventing hypoglycemia and hyperglycemia. Decision support as well as predictive analytics extend the personalized approach of the pathology and treatment plan and are free to the patient to make some informed decisions regarding their diet, physical activity, and dose changes. Moreover, by closely being monitored by the doctors and other healthcare practitioners, the intervention and support are promptly offered, so they encourage a team-based care model. Nevertheless, there are certain limitations to the widespread application of CGMs, including high costs and certain issues concerning ease of use that still deserve further development; however, further studies and advancements will certainly level those problems too and develop farther this type of technology.

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