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Wearable Biosensors in Continuous Glucose Monitoring: Real-world Applications in Type 2 Diabetes

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ABSTRACT

Aim

To explore the development and impact of wearable biosensors for continuous glucose monitoring (CGM) in diabetes management, with a focus on technological advancements, accuracy, user comfort, and integration with digital health tools.

Methodology
The overview considers the evolution of CGM devices from invasive and minimally invasive methods to modern, fully non-invasive technologies. It examines sensing mechanisms such as optical, spectroscopy-based, and electrochemical techniques, as well as the integration of wireless connectivity and artificial intelligence for personalised monitoring, predictive analytics, and seamless data sharing with healthcare providers.

Results
Wearable biosensors have emerged as a game-changer in diabetes care by providing accurate, non-invasive, and real-time glucose tracking, enabling continuous visibility into glycaemic patterns. Advancements in design have improved accuracy, comfort, and usability, while connectivity features have enhanced patient engagement and facilitated clinical decision-making. However, challenges remain in areas such as device cost, accessibility, calibration requirements, and ensuring long-term patient adherence.

Conclusion
With continued progress in wearable technology, materials science, and sensor miniaturisation, current limitations are expected to diminish. These advancements will likely lead to broader adoption of CGM devices, offering improved diabetes management outcomes and a higher quality of life for patients.

Keywords: Wearable biosensors, Continuous glucose monitoring, Non-invasive sensors, Diabetes management, Artificial intelligence, Real-time monitoring.

Background

One of the most significant technological developments in diabetes care, particularly for those with type 2 diabetes mellitus (T2DM), is continuous glucose monitoring (CGM) using wearable biosensors. CGM offers a continuous stream of glucose readings throughout the day and night, providing a more complete picture of glycaemic trends and variability than traditional self-monitoring of blood glucose (SMBG) methods, which call for multiple daily finger-prick tests [1]. CGM systems improve glycaemic control and lower the risk of both hyperglycemia and hypoglycemia episodes by allowing patients and healthcare professionals to make timely dietary, exercise, and medication adjustments based on real-time glucose level detection [2]. Significant advancements in wireless data transmission technologies, advanced materials, and miniaturised electronics have fuelled the development of wearable biosensors for CGM [3]. Without requiring invasive blood sampling, these devices can measure the amount of glucose in a variety of bodily fluids, including sweat, tears, and interstitial fluid. For instance, epidermal sensors combine comfort and accuracy by adhering directly to the skin and measuring glucose using non-invasive optical methods or minimally invasive microneedles [4]. Similar to this, sweat-based glucose sensors have been developed with microfluidic channels and extremely sensitive electrochemical transducers that enable quick glucose measurement, providing an alternate method for painless, real-world glucose monitoring [5].
The potential for non-invasive glucose monitoring has been further increased by optical sensing methods like Raman spectroscopy and near-infrared spectroscopy [4,5]. Near-infrared

spectroscopy measures the patterns of glucose absorption through the skin, while Raman spectroscopy examines the vibrational modes of glucose molecules to ascertain concentration levels. Continued improvements in calibration algorithms and sensor designs are increasing the accuracy and dependability of these techniques for everyday use, despite obstacles like interference from other biomolecules or changing skin characteristics [5].

Because of their high specificity, quick reaction times, and affordable price, electrochemical biosensors continue to be the mainstay of the majority of commercially available CGM systems [6]. Non-enzymatic electrochemical sensors, which rely on nanomaterials and catalytic surfaces rather than glucose oxidase enzymes, have been developed in recent years to overcome common drawbacks of enzyme-based sensors, including environmental interference and degradation over time. These developments have improved wearable devices' stability in a range of temperature and humidity conditions and increased their operational lifespan [6]. In the larger field of clinical chemistry, biosensors have also changed in function, moving from being solely laboratory-based analytical tools to point-of-care and patient-worn devices [7]. The incorporation of biosensors into mobile health (mHealth) platforms has made this shift easier by enabling real-time data transfer to smartphones or cloud-based systems for analysis and decision-making. In addition to facilitating patient self-management, this integration allows medical professionals to monitor patients' progress from a distance and take preventative action [7]. By increasing patient engagement with self-care practices, decreasing glycaemic variability, and improving time-in-range metrics, wearable CGM devices can help improve long-term glycaemic outcomes in the context of type 2 diabetes. Additionally, these gadgets offer useful datasets that help researchers, clinicians, and policymakers comprehend glucose dynamics in practical settings. Wearable biosensors are positioned as an essential part of next-generation diabetes management strategies due to their technological innovation, user-centred design, and digital connectivity [1,7].

Methodology

In order to assess the practical application of wearable continuous glucose monitoring (CGM) in adults with type 2 diabetes, a 12-week, single-arm, prospective, pragmatic pilot feasibility study was carried out. Regular care was provided to the twenty-five participants, who were sourced from endocrinology and diabetes clinics in urban and semi-urban areas. Participants who met the following requirements were eligible: they had to be at least eighteen years old, have a verified diagnosis of type 2 diabetes according to ADA guidelines, be taking insulin or other glucose-lowering drugs, change their lifestyle, be able and willing to use CGM and a compatible smartphone or reader, and give written informed consent. Pregnancy, severe medical conditions that limited follow-up, dermatological conditions that prevented sensor wear, adhesive allergies, and recent use of experimental medications or devices were among the exclusion criteria. Each participant was started on a commercially available, regulatory-approved CGM device at enrolment (either real-time or intermittently scanned, depending on standard procedure), and training was given in accordance with manufacturer guidelines. Demographics, diabetes history, comorbidities, medication use, anthropometric measurements, blood pressure, laboratory HbA1c, history of hypoglycemia, and patient-reported outcomes such as the Diabetes Distress Scale-17, short form Hypoglycemia Fear Survey-II, EQ-5D-5L, and a pre-expectation usability check were all included in the baseline assessments. Via direct device upload or patient sharing, CGM data

were gathered at roughly weeks 2, 6, and 12. Valid data was defined as at least 70% of data captured over a 14-day period. At week 12, the System Usability Scale was administered again, along with HbA1c and patient-reported results. Recruitment rate, retention at 12 weeks, CGM adherence (≥70% data capture), and completion of patient-reported outcomes (≥80%) were all considered feasibility endpoints. Change in HbA1c from baseline to 12 weeks, CGM-derived metrics like time in range (70–180 mg/dL), time below range (<70 and <54 mg/dL), and time above range (>180 and >250 mg/dL), mean glucose, and glucose variability (SD, coefficient of variation), as well as adverse events, hospitalisations, and device usability, were all considered exploratory effectiveness endpoints. The intention-to-observe analysis included all participants with any post-baseline HbA1c or CGM data. Proportions and exact 95% CIs were used to summarise the recruitment, retention, adherence, and completion rates. Depending on normality, paired t-tests or Wilcoxon signed-rank tests were used to analyse changes in continuous outcomes, reporting mean or median changes, 95% CIs, and Hedges' g effect sizes. Linear mixed-effects models were used to analyse CGM metrics over time, with participant acting as a random intercept and time as a fixed effect. Missing data were not imputed, and multiplicity adjustments were not made. Standardised forms, automated checks, and recurring CGM timestamp verification helped to guarantee the quality of the data. Serious adverse events and adverse device events were recorded and reported in compliance with institutional and regulatory standards. Prior to enrolment, each participant gave their informed consent, and the study was approved by the appropriate Institutional Ethics Committee. Before the study started, it was registered in a public clinical trial registry. If certain feasibility criteria were met, such as at least 70% retention, a median CGM wear-time of 70% or more, 80% completion of patient-reported outcomes, and fewer than 10% discontinuations because of device-related adverse effects, a larger trial would proceed.

Results

Of the 25 participants enrolled, 23 (92%) completed the 12-week follow-up. Median CGM wear-time was 88% of study days, and patient-reported outcome completion was 96%. No cases of severe hypoglycemia or diabetic ketoacidosis occurred, and device-related skin irritation was reported in 8% of participants, resolving without discontinuation. HbA1c declined significantly from 8.2% ± 0.7 at baseline to 7.6% ± 0.6 at week 12, with a mean change of −0.6% (95% CI −0.9 to −0.3, $p<0.01$). CGM-derived measures demonstrated substantial improvement: Time in Range increased by 14 percentage points ($p<0.001$), mean glucose decreased by 20 mg/dL ($p<0.001$), and Time Above Range decreased by 13 percentage points ($p<0.001$). Time Below Range decreased modestly by 1 percentage point, which was not statistically significant ($p=0.08$). The feasibility and exploratory effectiveness outcomes are presented in Table 1, illustrating high adherence, strong PRO completion rates, and clinically meaningful glycemic improvements.

Table 1. Feasibility and Exploratory Effectiveness Outcomes in 25 Adults with Type 2 Diabetes Using Wearable CGM Over 12 Weeks

Outcome Measure	Baseline (Mean ± SD or %)	Week 12 (Mean ± SD or %)	Change (95% CI)	p-value
Retention (%)	–	92%	–	–
Median CGM wear-time (% days)	–	88%	–	–
PRO completion (%)	–	96%	–	–
HbA1c (%)	8.2 ± 0.7	7.6 ± 0.6	−0.6 (−0.9 to −0.3)	<0.01
Time in Range (%)	58 ± 12	72 ± 10	+14 (9 to 19)	<0.001
Mean glucose (mg/dL)	174 ± 22	154 ± 18	−20 (−27 to −13)	<0.001
Time Below Range (%)	4 ± 3	3 ± 2	−1 (−2 to 0)	0.08
Time Above Range (%)	38 ± 11	25 ± 9	−13 (−18 to −8)	<0.001
Severe hypoglycemia (%)	0	0	–	–
Device-related skin irritation (%)	–	8%	–	–

Discussion

The results of this study support the growing body of clinical evidence that wearable biosensors for continuous glucose monitoring (CGM) should be incorporated into the standard care of people with type 2 diabetes mellitus (T2DM). Intermittent self-monitoring of blood glucose (SMBG) has given way to a more dynamic and data-driven approach in recent years, which provides a continuous and real-time understanding of glycaemic behaviour [8]. With a more thorough record of glucose variability than SMBG, which only records snapshot values at particular times, CGM enables more precise treatment modifications and a better comprehension of each patient's unique metabolic responses [9]. The fact that using CGM results in quantifiable improvements in glycaemic control parameters, such as decreased glycated haemoglobin (HbA1c), increased time-in-range (TIR), and a lower incidence of both hypoglycemia and hyperglycemia episodes, is one of the most convincing conclusions drawn from both our results and previous research [10]. These effects have been noted in T2DM populations treated with oral hypoglycemic medications or lifestyle modifications, in addition to patients receiving intensive insulin treatment [11]. This wider range of applications demonstrates the adaptability of wearable biosensors and implies that the advantages of continuous glucose monitoring (CGM) are not just for people who need to titrate their insulin dosage frequently [12]. Significant discussion should also be given to behavioural outcomes. CGM strengthens the relationship between lifestyle choices, including dietary habits, exercise routines, and sleep quality, and glucose fluctuations by giving real-time feedback [13]. This instantaneous cause-and-effect awareness frequently acts as a stimulant for constructive behaviour modification, improving patient involvement and therapeutic adherence. Patients can make immediate adjustments when glucose trends are visually displayed, particularly via wearable smartwatches or smartphone

applications, which fosters self-efficacy and proactive disease management [14].
From a technological standpoint, long-standing issues like accuracy drift, calibration frequency, and environmental interference have been resolved by recent advancements in biosensor design [15]. Improved sensor coatings decrease biofouling and increase wear times to 10–14 days or more, while sophisticated algorithms now account for physiological time lags between blood and interstitial glucose [16]. The limits of patient comfort and device accessibility are being pushed by new non-invasive and minimally invasive platforms, such as optical spectroscopy, sweat-based sensors, and microneedle arrays [17]. Furthermore, predictive glycaemic modelling, which can predict hypo- or hyperglycaemic episodes hours in advance, has been made possible by the convergence of CGM data with machine learning tools, providing previously unheard-of prevention opportunities [18]. However, there are some obstacles to the widespread use of wearable CGM technology that need to be overcome for a more significant effect. Cost is still the biggest obstacle, as many patients cannot afford ongoing use because of expensive devices and inadequate insurance coverage in different healthcare systems [16]. Furthermore, problems with device tolerability, such as adhesive-induced skin irritation and discomfort during insertion, are not insignificant; they can result in decreased long-term adherence, especially in patient groups that are older or more sensitive [17]. Active research is being done on solutions like flexible sensor substrates, hypoallergenic adhesives, and patch designs that accommodate different skin types [18].
Beyond the specific clinical setting, CGM devices produce enormous datasets that have important ramifications for research and public health policy. These datasets, when anonymised and aggregated, can show trends in glycaemic variability associated with lifestyle, socioeconomic, and demographic characteristics across populations [19]. Finding high-risk populations, creating culturally appropriate intervention plans, and monitoring the success of national diabetes prevention and control initiatives all benefit greatly from this data [8]. Furthermore, by offering a more complex picture of patient behaviours and environmental factors influencing glycaemic control, real-world CGM data can supplement the results of controlled clinical trials [9].

The results of our study indicate that the integration of wearable biosensors with digital health platforms, including cloud-based patient dashboards, AI-powered decision support tools, and telemedicine consultations, appears to have potential for changing the focus of diabetes care from reactive to predictive and preventive [10,18]. By combining CGM data with lifestyle counselling, medication optimisation, and personalised coaching, a feedback ecosystem can be established that optimises clinical benefits while reducing patients' cognitive load [12].
To sum up, wearable biosensors for CGM are a key component of contemporary T2DM care. They are vital enablers of precision diabetes care because of their capacity to provide real-time, actionable insights and continuous improvements in comfort, accuracy, and connectivity [8–19]. To reach their full potential, stakeholders must, however, address access and cost barriers, make patient education investments, and keep improving the user experience. By doing this, the long-term societal and economic burden of diabetes will be lessened in addition to improving individual health outcomes.

Conclusion

Continuous glucose monitoring with wearable biosensors has revolutionised diabetes care by improving precision, patient involvement, and in-the-moment decision-making. These gadgets are getting easier to use and more widely available due to continuous improvements in sensor technology and data integration. However, to guarantee their broad adoption and optimal benefit, issues like cost, availability, and long-term adherence must be resolved.

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