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Review article

Insulin delivery devices in diabetes management: Applications and advancements

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ABSTRACT

With continuous advancements in diabetes management technology, insulin delivery devices have become increasingly central to the treatment of diabetes. This review discusses the applications and development of various insulin delivery technologies, including insulin pens and pumps, in the management of type 1 diabetes (T1DM) and type 2 diabetes (T2DM). Insulin pens are widely used among individuals with T2DM due to their ease of use and dosing accuracy. The recent development of smart insulin pens has further enhanced patient adherence and glycemic control. Insulin pumps, particularly patch pumps, provide more precise glucose management for individuals with T1DM and select T2DM patients, significantly reducing glycemic variability and the risk of hypoglycemia. Patch pumps, as an innovative insulin infusion device, are particularly suitable for patients requiring discreet and convenient use, owing to their compact, lightweight, and tubeless design. This is especially pertinent for the large population of individuals with T2DM. However, mechanical patch pumps still require further optimization, particularly in displaying infusion volume and key operational parameters, to facilitate real-time monitoring and timely therapeutic adjustments by both patients and clinicians. This review summarizes the advantages and limitations of different types of insulin delivery devices and explores their potential role in clinical practice. Further advancements in these systems are expected to offer safer, more convenient, precise, and cost-effective treatment options for diabetes management.

1. Introduction

Diabetes is a chronic metabolic disorder defined by impaired regulation of carbohydrate metabolism, leading to persistent hyperglycemia. In this condition, glucose utilization as a primary energy source is compromised, while excessive glucose production occurs due to dysregulated gluconeogenesis and glycogenolysis, culminating in elevated blood glucose levels.[1] Diagnosis is typically based on elevated plasma glucose concentrations or increased glycated hemoglobin (HbA1c) levels. Diabetes encompasses several subtypes, including type 1 diabetes (T1DM), type 2 diabetes (T2DM), gestational diabetes, and forms secondary to genetic defects, pancreatic disease, or drug exposure.[2]

T1DM primarily arises from autoimmune destruction of pancreatic β-cells, leading to absolute insulin deficiency. Latent autoimmune diabetes in adults (LADA) also falls within this category, characterized by slower progression.[3–6] T2DM, in contrast, involves a progressive decline in insulin secretion coupled with insulin resistance, often occurring in the context of metabolic syndrome.[7,8] Additionally, specific diabetes subtypes can result from monogenic syndromes (e.g., neonatal diabetes, maturity-onset diabetes of the young), exocrine pancreatic diseases (e.g., cystic fibrosis, pancreatitis), or medication-induced hyperglycemia (e.g., glucocorticoids, antiretroviral therapy, post-organ transplantation). Gestational diabetes typically emerges during the second or third trimester of pregnancy in previously non-diabetic individuals, but may overlap with other forms, such as T1DM, diagnosed during pregnancy.[9]

The increasing prevalence of diabetes and its associated complications represents a major global health crisis. According to the International Diabetes Federation (IDF), in 2015, approximately 415 million adults aged 20 to 79 years—equivalent to one in 11 adults worldwide—had diabetes.[10] This number is projected to rise to 642 million by 2040, with the largest increase expected in regions transitioning from low to middle income.[10] Importantly, these projections may underestimate the true burden

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of diabetes, particularly in regions experiencing rapid epidemiological changes.[11] Notably, over 90% of all diabetes cases are T2DM.[12,13]

Recent years have seen substantial advancements in insulin therapy, including the development of ultra-long-acting basal insulins[14,15] and ultra-rapid-acting mealtime insulins.[16,17] These innovations have significantly enhanced glycemic control while minimizing the risk of hypoglycemia in patients. The methods of insulin administration have also evolved, moving from traditional vials and syringes to advanced insulin pens and pumps, which offer increased convenience and precision in insulin delivery.[18] Early insulin delivery systems, such as metal and glass syringes, were cumbersome, limiting their widespread use. The introduction of disposable syringes and insulin pens significantly improved adherence by enhancing dosing accuracy, reducing discomfort, and increasing safety, leading to broad adoption.[19–21]

In cases where standard glycemic targets are not met or recurrent hypoglycemia is observed, intensive insulin treatment regimens such as multiple daily injections (MDI) or continuous subcutaneous insulin infusion (CSII) may be employed. CSII, which aims to replicate the physiological secretion pattern of pancreatic insulin, allows for tighter glucose control, reduced glycemic variability, and diminished hypoglycemia risk.[22] Among T1DM patients, insulin pump therapy has demonstrated superior glycemic control and stability compared with MDI, without increasing hypoglycemia risk.[23–27] For individuals with T2DM who fail to achieve glycemic targets with MDI, CSII provides a promising alternative, yielding a more physiological insulin profile. Evidence suggests that T2DM patients can derive similar benefits from CSII as those seen in T1DM, especially in selected populations.[28–30]

The emergence of advanced insulin delivery technologies has fundamentally transformed diabetes management, offering patients—particularly those requiring precise glycemic control—more individualized and effective treatment options. This article explores the principles, development, and clinical applications of modern insulin delivery devices, offering a comprehensive overview of insulin infusion technologies and their role in optimizing diabetes care.

2. Principles and development of insulin delivery devices

Insulin delivery devices are integral tools for diabetes management, designed to deliver insulin continuously or intermittently to mimic the pancreas's natural insulin secretion and maintain stable blood glucose levels. Recent research has focused on achieving stricter glycemic control while minimizing the occurrence of hypoglycemia, particularly by optimizing insulin delivery to emulate endogenous pancreatic insulin secretion. With continuous technological advancement, insulin delivery devices have not only improved the precision and accuracy of insulin administration but have also significantly reduced treatment invasiveness and patient burden. The primary types of insulin delivery devices include insulin pens and insulin pumps. Fig. 1 illustrates commonly used insulin delivery devices, and Table 1 summarizes the types, advantages, disadvantages, target populations, and clinical applications of these devices.

2.1. Insulin pens

The introduction of insulin pens addressed many of the inconveniences and inaccuracies associated with traditional syringes and vials used for insulin administration. Early insulin injection devices, consisting of glass or metal syringes with reusable needles, were not only imprecise but also poorly accepted due to injection-related anxiety.[31] To overcome these challenges, pharmaceutical companies developed insulin pens as a more convenient and accurate alternative. Insulin pens are available in two main types: reusable and disposable prefilled models. Insulin pens are categorized into reusable and disposable prefilled models, with reusable pens utilizing replaceable insulin cartridges and disposable pens discarded after use.[32]

Since Novo Nordisk introduced the first reusable insulin pen, NovoPen®, in 1985, insulin pen devices have undergone several generations of improvement and optimization. Each new generation has brought significant enhancements in user experience, dose accuracy, and ease of operation for patients.[33–35] Additionally, some insulin pens offer half-unit dose increments, which are especially beneficial for children and elderly patients requiring more refined dose adjustments.[36,37]

Recent advancements in digital technology have led to the development of smart insulin pens, enhancing insulin administration convenience and safety. Smart insulin pens can record the dosage and timing of injections and use Bluetooth technology to transmit data to mobile devices, allowing patients to track insulin use and reduce the risk of missed doses. These devices enable more precise insulin management and reduce uncertainty during injections, thereby improving overall glycemic control.[38–40]

2.2. Insulin pumps

Insulin pumps, or CSII devices, represent a major breakthrough in diabetes treatment. Insulin pumps use capillary blood glucose self-monitoring to regulate glucose control, providing greater patient satisfaction and demonstrating superior outcomes compared with MDI. Over the past 40 years, significant progress has been made in insulin pump technology, which is now widely used in modern diabetes care. Electronic insulin pumps are compact automated devices that deliver rapid-acting insulin continuously over 24 h, more closely mimicking physiological insulin secretion. The system consists of a disposable insulin reservoir and an infusion set, which includes a subcutaneous catheter and tubing connecting the reservoir to the catheter. One of the primary advantages of insulin pumps is their ability to deliver basal insulin at a predetermined rate, typically set on an hourly basis. Insulin pumps also allow for personalized mealtime insulin dosing based on carbohydrate intake and provide correction doses for hyperglycemia, with an inbuilt calculator that accounts for insulin-on-board and insulin action time.[41,42]

Currently, there are three main types of insulin pumps: traditional pumps, patch pumps, and implantable pumps, each offering unique advantages tailored to the diverse needs of patients with diabetes.

2.2.1. Traditional insulin pumps

Traditional insulin pumps are small electronic devices that deliver rapid-acting insulin continuously through a subcutaneous infusion set ("infusion kit" or "infusion catheter") inserted into subcutaneous tissue.[43] Typically, the infusion set is connected to the pump by plastic tubing, and insulin is delivered through the tubing into the subcutaneous tissue. The pump itself, which usually has control features, can be worn on the body or placed in a pocket. The primary benefit of traditional electronic pumps is their ability to continuously deliver basal insulin at highly customizable rates, adjustable in increments as small as 0.01 units per hour to meet 24-h insulin needs. This precision can help better simulate physiological insulin secretion, aiding in maintaining stable glycemic levels. However, traditional electronic pumps have certain limitations. The use of tubing to connect the pump to the infusion site may cause discomfort or restrict movement during physical activities. However, their tubing may cause discomfort, restrict movement, or become blocked, kinked, or dislodged, potentially compromising insulin delivery.

2.2.2. Patch pumps

Patch pumps were designed to overcome the issues associated with infusion tubing in traditional pumps. These pumps do not require tubing and instead deliver insulin through a device that adheres directly to the skin, offering advantages such as smaller size, enhanced discretion, ease of use, and reduced cost.[44] Patch pumps are lighter and allow patients to move more freely without concerns about tubing, thus improving quality of life. Despite these benefits, patch pumps also have limitations, such as the need for frequent changes (every 2–3 days), which can increase cost and complexity. Patch pumps may also experience infusion problems, such as catheter blockages, subcutaneous air bubbles, and formation of

Fig. 1. Illustration of insulin delivery devices. A: Insulin Pen; B: Traditional Insulin Pump; C: Patch Pump; D: Implantable Insulin Pump.

subcutaneous nodules from repeated needle insertions, all of which can affect insulin delivery efficiency.[45] Nevertheless, patch pumps are well-suited for patients who prioritize convenience and portability, particularly those with T2DM.

Currently, patch pumps are classified into mechanical and software-driven types based on their mode of operation. Mechanical patch pumps, such as CeQur and V-Go, rely on mechanical structures for insulin delivery and do not require electronic components, making them cost-effective and simple to operate. Recent advancements in this area include Patent No. CN202411057395.9, which introduces a mechanical patch pump with a dual symmetrical compression system, designed to enhance infusion precision and minimize fluctuations in basal insulin delivery. Similarly, Patent No. CN202411282861.3 describes a mechanical patch pump integrating a modular infusion system with one-way valve control, improving the accuracy of bolus dosing and ensuring stable insulin administration. Such pumps are suitable for patients with stable insulin needs that do not require frequent adjustments.

In contrast, software-driven patch pumps, such as Omnipod, connect wirelessly to smart devices (typically via an app) and allow precise control of insulin delivery, including customized settings and adjustments. These pumps are particularly beneficial for those who need frequent adjustments to basal rates and mealtime doses. The primary advantage of these devices lies in their precise insulin management capabilities, allowing patients to control dosing remotely, reducing the need for direct interaction with the pump. However, software-driven patch pumps are generally more expensive and require greater technical proficiency from patients.

2.2.3. *Implantable Insulin Pumps*

Implantable insulin pumps are more complex devices that are surgically placed inside the patient's body, continuously delivering insulin into the peritoneal cavity. The highly vascular peritoneal cavity allows for more rapid and stable insulin absorption compared to subcutaneous administration, making implantable pumps suitable for patients with poor adherence to external insulin infusion devices or those requiring highly precise and stable insulin delivery. Implantable pumps offer several advantages, such as long-term insulin infusion without the inconvenience of external devices, thereby enabling greater freedom for daily activities. However, challenges include surgical risks, postoperative complications, and high maintenance costs.[46]

Table 1
Summary of types of insulin delivery devices, their advantages, disadvantages, applications, and target populations.

Device Type	Advantages	Disadvantages	Target Population	Clinical Application
Insulin Pens	1. Convenient and user-friendly; 2. Accurate dosing; 3. Smart pens facilitate integration with apps, enhancing adherence.	1. Lack of automation; 2. Requires patient diligence; 3. May be unsuitable for patients needing frequent dosage.	1. T2DM patients needing simple dosing tools; 2. Suitable for elderly and those with visual or dexterity limitations.	1. Effective in managing T2DM; 2. Appropriate for those requiring flexible and precise dose adjustments.
Traditional Insulin Pumps	1. CSII enables physiological insulin delivery; 2. Customizable basal and bolus rates to meet patient needs.	1. Bulky and may restrict movement; 2. Tubing can kink or become disconnected; 3. Regular catheter changes needed; 4. High cost	T1DM patients requiring intensive insulin management and frequent dose adjustments.	Primarily used in T1DM for patients with poor glycemic control on MDI.
Patch Pumps	1. Tubeless design, lightweight and discreet; 2. Greater mobility; 3. More affordable compared to traditional pumps, simple to operate.	1. Frequent device replacement required; 2. Potential for catheter occlusion; 3. Limited control of basal rates compared to traditional pumps.	1. T2DM patients prioritizing convenience and mobility; 2. Young adults preferring a modern solution; 3. Suitable for those with stable insulin needs.	1. Well-suited for T2DM patients needing easy, flexible insulin delivery; 2. Used for prandial insulin in social environments to reduce injection-related stigma.
Implantable Insulin Pumps	1. Consistent, long-term insulin infusion; 2. Improved insulin absorption 3. Less patient intervention required compared to external pumps.	1. High cost; 2. Requires surgical implantation; 3. Risk of postoperative complications; 4. Requires frequent medical follow-ups.	1. Patients with significant difficulties in daily insulin management; 2. Preferable for those needing stable and predictable insulin delivery.	Effective in maintaining stable glycemic levels without reliance on patient compliance.

3. Application of insulin delivery devices in diabetes management

3.1. Application of insulin delivery devices in T1DM

T1DM accounts for 5%–10% of all diabetes cases globally. Despite its increasing incidence, no cure is currently available, necessitating lifelong management.[47] Flexible insulin delivery methods have become increasingly popular. Insulin pens were introduced in 1981 as convenient and easy-to-use injection devices, widely used in MDI therapy and continue to evolve. However, no studies have yet demonstrated the superiority of smart pens over traditional pens.

In the past two decades, the use of insulin pump therapy has steadily increased. Data from large diabetes registries indicate that in Western countries, where insulin pump use is more prevalent, 40%–60% of individuals with T1DM use insulin pumps.[48,49]

Smart electronic insulin pumps are equipped with multiple auxiliary functions, such as calculators for mealtime and correction doses, options for immediate or delayed bolus administration, and temporary basal rates to accommodate changes in insulin requirements due to physical activity or illness. These features may improve glycemic control outcomes, including reducing HbA1c levels and minimizing postprandial glucose variability.[50,51] In adults with T1DM, insulin pump therapy compared with MDI has been associated with a modest reduction in HbA1c levels of 0.3%–0.6%, particularly in those with poor control on MDI, where pump therapy often leads to significant improvements in HbA1c.[25,52,53] For patients with suboptimal glycemic control on MDI therapy, transitioning to insulin pump therapy frequently results in substantial and clinically meaningful improvements in HbA1c levels.[52] The risk of severe hypoglycemia is similar between the two methods, or slightly lower among pump users, who generally report a better quality of life than those using MDI.[25,26,52–54]

Although insulin pumps are attractive to pediatric and adolescent patients due to their flexibility and customizable insulin delivery, meta-analyses and systematic reviews of randomized controlled trials (RCTs) involving pediatric populations have not shown the same degree of benefit as in adult studies. Overall, pediatric pump users exhibit slightly lower HbA1c levels, with a comparable risk of severe hypoglycemia to those on MDI therapy.[25,55] Insulin requirements are generally lower with pump therapy,[25,55] and the incidence of diabetic ketoacidosis (DKA) does not differ significantly between pump and MDI users.[56] Among children and adolescents using pumps (and their parents), quality of life and treatment satisfaction are comparable to or higher than those of patients using MDI.[53] Overall, meta-analyses of RCTs cautiously favor insulin pump therapy over MDI for both pediatric and adult T1DM patients.

3.2. Application of insulin delivery devices in T2DM

Insulin pens are currently the most widely used method of insulin administration among patients with T2DM.[57] Over the past decade, significant advances have been made in insulin pen design, including the incorporation of "memory" functions that store and display previous injection times and dosage information. This feature is particularly useful for patients with cognitive impairment or those who struggle to actively participate in diabetes management due to complex dosing regimens.[58] More importantly, smart insulin pens can integrate these features with continuous glucose monitoring (CGM) data and upload information to online platforms, allowing healthcare professionals to remotely review and adjust treatment plans.[39] Studies have shown that poor adherence to insulin dosing is associated with inadequate glycemic control; thus, smart pens may offer an effective way to identify patients in need of education and behavioral intervention at an early stage. However, no studies have specifically evaluated the impact of smart pens on glycemic control, quality of life, or cost-effectiveness in patients with T2DM.

3.2.1. Traditional insulin pumps in T2DM

In recent years, the number of T2DM patients using insulin pumps has been increasing,[59] largely because the benefits of CSII observed in T1DM may also apply to patients with T2DM. Several reviews have summarized clinical trials assessing the effects of CSII in T2DM, indicating that insulin pumps may provide significant therapeutic benefits in this population. However, differences in trial design, methodology, pump selection, and participant characteristics have led to variability in study results and quality. Furthermore, most pumps used in these trials were not specifically designed for T2DM. In the OpT2mise study, a two-month run-in period with a standardized titration protocol (including adjustments to basal and prandial insulin) was implemented to optimize dosing, after which patients with suboptimal glycemic control were randomized to either the CSII or MDI group.[60] In the CSII group, 50% of the total daily insulin dose was initiated as basal infusion. Significant improvements in glycemic control observed after six months of CSII therapy were sustained during the subsequent six-month follow-up, with similar improvements seen in patients who switched from MDI to CSII after the initial six months.[61] Other trials have also incorporated run-in periods before CSII initiation, although the duration of these periods varied.[62–64] Currently, there is a lack of clinical data comparing different types of insulin pumps and their effects in various populations.

3.2.2. Mechanical patch insulin pumps in T2DM

Compared to traditional insulin pumps, mechanical patch insulin pumps offer advantages such as smaller size, lighter weight, tubeless design, soft subcutaneous catheters, and no need for a smart electronic device. However, limitations include the need for further development in basal insulin regulation and semi-automated or fully automated infusion capabilities. Current electronic insulin pump systems used in T1DM include many advanced features that may not be necessary for T2DM treatment and could complicate device use. Functions such as precise carbohydrate-based prandial insulin dosing or multiple basal rates may not be used by most T2DM patients or may require significant time investments in patient education by healthcare professionals.[64–66] Additionally, the complexity of pump operation and high costs may deter T2DM patients from using insulin pumps or even affect the uptake of CSII therapy.[65,67] Data from previous trials indicate significant variability in patient acceptance of insulin pump therapy. Because CSII therapy requires comprehensive understanding by both users and healthcare providers of how to use the pump and its functions, ongoing education and intensive training are critical for the adoption of smart software (app)--based electronic insulin pumps.[68,69] A lack of education and training may lead to improper use of pump functions, increasing the risk of complications such as ketoacidosis or severe hypoglycemia.[68,69] In comparison, mechanical patch pumps, with their simpler functionality, are easier for patients to operate and are more cost-effective, thereby promoting wider adoption.

Mechanical patch insulin pumps specifically designed for T2DM have been introduced in Europe and the United States.[70] A clinical trial by Mader et al evaluated the safety and efficacy of the PAQ (CeQur) mechanical patch insulin pump in T2DM patients. The results showed a significant reduction in HbA1c (from 8.6 % to 7.1 %, $P < 0.0001$), an increase in total daily insulin dose by 12.1 units ($P = 0.0058$), and increased frequency of prandial insulin use ($P = 0.0081$).[71] In addition to safety and efficacy, a study by Hermanns et al assessed the effectiveness of PAQ in reducing psychological barriers to insulin therapy and improving adherence among T2DM patients previously on MDI therapy.[64] Preliminary findings indicated that PAQ reduced barriers to insulin use, particularly in terms of fear of injections, feelings of stigma, and improved expectations for treatment outcomes. Specifically, the device shortened insulin administration time and allowed for easier dosing at appropriate times without affecting daily activities or mobility.[64] Other studies have reported high practicality of mechanical patch pumps. Compared to insulin pens, 77.8 % of patients preferred using mechanical patch pumps for prandial insulin delivery, over 90 % of users found it comfortable to administer insulin "inconspicuously" in social settings, 88.6 % reported a reduction in the diabetes-related supplies they needed to carry, and 84.4 % felt that the mechanical patch pump provided greater freedom in diabetes management.[64,72,73] Overall, these pumps significantly reduce barriers to insulin therapy and enhance overall patient satisfaction with insulin treatment.

Valeritas's V-Go is another example of a mechanical patch insulin pump. Sutton et al conducted a retrospective analysis to evaluate the long-term clinical outcomes of V-Go in adult diabetes patients.[74] The results demonstrated a significant reduction in HbA1c by 1.67 % after 14 months of V-Go use ($P < 0.0001$), while total daily dose of insulin decreased by 17 units per day in patients previously on MDI at baseline ($P < 0.0001$). Moreover, the use of V-Go resulted in significant pharmacy cost savings, with monthly reductions of approximately USD 25 per patient. Overall, patients using V-Go exhibited significant improvements in HbA1c and insulin dosage, along with enhanced adherence to insulin therapy.[74] Due to its advantages in clinical outcomes, studies have analyzed the impact of V-Go on diabetes-related medication costs in T2DM patients. Results indicate that compared with MDI therapy, the V-Go group experienced a smaller increase in diabetes medication costs (mean increase of USD 341, compared with USD 1628 in the MDI group, $P = 0.012$). Additionally, the incremental cost per 1 % reduction in HbA1c was USD 695.61 lower for V-Go compared with traditional insulin pumps.[75,76] The convenience and effective glycemic control associated with V-Go make it a promising option for optimizing insulin therapy.[77]

3.3. Application of insulin delivery devices in pregnant patients with diabetes

In early pregnancy, women with diabetes are generally more sensitive to insulin, necessitating close monitoring of blood glucose levels to avoid hypoglycemia. As pregnancy progresses beyond 16 weeks, insulin resistance increases among women with pre-existing diabetes, with insulin requirements potentially changing weekly. Insulin demand may also rise at various stages of pregnancy. Skajaa et al.[78] reported that, with increasing parity, daily insulin requirements among mothers with type 1 diabetes exhibited a stepwise increase. Adjusted data indicated that compared to mothers experiencing their first pregnancy, those with one, two, or three to four pregnancies had increased insulin requirements by 13 %, 20 %, and 36 %, respectively. For women with type 2 diabetes managed with diet, oral medication, or basal insulin alone, education on intensive insulin management is crucial before or during pregnancy to achieve optimal glycemic control. Insulin remains the cornerstone of managing diabetes during pregnancy, as it effectively reduces blood glucose levels and is safe for use during pregnancy given that it does not cross the placenta.

In a study involving 93 participants, the outcomes of insulin pen versus syringe injection were compared. The findings indicated that women using insulin pens had a lower rate of cesarean delivery, although there were no significant differences in the incidence of macrosomia. However, the study did not report composite outcomes including perinatal mortality, preeclampsia, fetal anomalies, delivery trauma (e.g., shoulder dystocia, nerve palsy, and fractures), or neonatal morbidity. The study's small sample size and limitations in study design contributed to a high or unclear risk of bias, resulting in low-quality evidence.

Both MDI and CSII are effective management strategies during pregnancy. Despite the evident flexibility of insulin pumps for prandial insulin infusion, insufficient evidence currently exists to recommend one method over the other.[79] When CSII is planned, it is advisable to initiate it before conception to allow the patient to become accustomed to the pump and achieve tight glycemic control prior to pregnancy. Furthermore, women using CSII should develop a subcutaneous insulin contingency plan in case of pump failure. The CONCEPTT trial conducted a pre-specified analysis comparing glycemic control and pregnancy outcomes between women with type 1 diabetes using MDI and CSII. The results showed that the MDI group had better glycemic control, lower rates of gestational hypertension, neonatal hypoglycemia, and neonatal intensive care unit admission, despite the insulin delivery method not being randomly assigned.[80]

3.4. Application of insulin infusion devices in perioperative patients

In patients with type 1 diabetes, continuous basal insulin infusion is critical, particularly during the perioperative period, to prevent diabetic ketoacidosis. If a patient using an insulin pump discontinues pump infusion perioperatively, insulin injection must immediately follow to prevent ketoacidosis. Patients for whom pump infusion will be stopped should have their daily basal insulin requirement clearly documented preoperatively, enabling timely prescription of long-acting (sustained-release) insulin and provision of doses based on established insulin replacement protocols. In outpatient or short-duration surgeries, continued use of the insulin pump for basal infusion is recommended when feasible, akin to patients maintaining long-acting insulin during surgery. If hyperglycemia occurs intraoperatively, it can be corrected using a basal-bolus regimen with subcutaneous rapid-acting insulin.

If the patient is using a personal insulin pump, the pump should be removed at the onset of surgery, followed by immediate initiation of intravenous insulin infusion (IVII) to maintain continuous insulin supply.[81] During the postoperative period, transitioning from intravenous insulin to subcutaneous insulin requires a basal-bolus regimen, which closely mimics the physiological function of a normal pancreas: (i) basal secretion is simulated with long-acting insulin, and should be continued as soon as intravenous insulin is discontinued; (ii) prandial secretion is simulated with rapid-acting insulin, with doses adjusted according to carbohydrate intake. Compared with intermittent short-acting insulin injections, this regimen significantly improves postoperative glycemic control and reduces the incidence of postoperative complications.[82] The initial dose of postoperative long-acting insulin should range between 0.3 and 1.5 IU/kg, depending on the specific study.[83] Several models have been proposed to ensure a smooth transition from IVII to subcutaneous insulin. The most commonly used model, proposed by Avanzini et al.,[84] suggests transitioning after blood glucose levels have stabilized for 24 h and the patient has resumed oral intake. Typically, half of the total intravenous insulin dose is used for long-acting insulin, with the other half for prandial rapid-acting insulin. Some studies recommend using 80 % of the intravenous dose for long-acting insulin, with an initial dose of rapid-acting insulin administered at the first meal.[85] Lazar et al.[86] argue that the transition should occur only when intravenous insulin infusion rates fall below 3 U/h, as higher infusion rates may increase the risk of postoperative complications. For patients using personal insulin pumps, reconnection should occur as soon as the patient is able to self-manage insulin delivery. If self-management is not possible, a basal-bolus regimen should be initiated immediately, using subcutaneous injections for insulin administration.[87]

4. Conclusion

This review systematically explored the application and development of insulin delivery devices in diabetes management, highlighting advances and clinical value of technologies such as insulin pens and pumps. Insulin pens, as one of the earliest insulin delivery tools, have been widely used among patients with T2DM due to their convenience and precision. Recent advancements in smart insulin pens have further enhanced patient adherence and glycemic control, particularly in individuals with cognitive impairments or complex dosing regimens. Although insulin pens have shown promise in improving glycemic management, their cost-effectiveness and long-term benefits compared with newer insulin pumps require further evaluation.

The introduction of insulin pumps has provided more precise glucose management for patients with T1DM and certain patients with T2DM, effectively reducing glycemic variability and the risk of hypoglycemia. Insulin pumps demonstrate significant advantages, particularly in patients with poor long-term control or frequent hypoglycemia. The development of mechanical patch insulin pumps offers an innovative and unique method of insulin delivery, especially for T2DM patients. These new mechanical patch pumps are notable for their lightweight, discreet, and easy-to-use design, significantly reducing psychological barriers to insulin therapy and enhancing quality of life. The tubeless design of mechanical patch pumps mitigates risks associated with catheter dislodgement or occlusion, offering enhanced convenience and mobility.

However, further technological refinement of mechanical patch insulin pumps is required. Although these pumps utilize a purely mechanical structure with microfluidic technology to control insulin delivery without complex electronics, improvements are needed to ensure real-time monitoring of insulin infusion. Optimizing the display systems of patch pumps to effectively provide reliable delivery data will enhance both patient confidence and clinical decision-making. Additionally, while portability is a core advantage of mechanical patch pumps, challenges such as subcutaneous tubing occlusion and device wear duration must be addressed to improve device stability and user experience. Tubing occlusion, in particular, poses a risk of disrupted insulin delivery, which could adversely affect glycemic control, making design improvements crucial.

Overall, the continuous evolution of insulin delivery devices has expanded personalized and precise treatment options, demonstrating substantial clinical value, particularly for patients unable to achieve optimal glycemic control with oral antidiabetic agents. Mechanical patch pumps, with their simplicity and potential to enhance quality of life, represent a promising innovation in diabetes management. With ongoing technological innovation, mechanical patch pumps are expected to offer even safer, more convenient, and precise treatment experiences, ultimately enhancing diabetes management outcomes.

CRediT authorship contribution statement

Runhuang Yang: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Conceptualization. **Zongwen Yang:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Conceptualization. **Jingnan Chi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Investigation, Conceptualization. **Ya Zhu:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

Runhuang Yang, Zongwen Yang, Jingnan Chi, and Ya Zhu are employees of Beijing Sinotech & wellcare Technology Development Co., LTD.

Data availability

Not applicable.

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