CZECHOWSKA, Katarzyna, ŚWIERCZEWSKA, Aleksandra, KOMASARA, Piotr, NOWAKOWSKA, Julia, SĘDEK, Aleksandra, MERCHEL, Lena, BEDNAREK, Ilona, LACH, Sylwia, BŁĄD, Karol Seweryn and KAŁUŻA, Kinga. Innovations in Pharmacotherapy of Diabetes: A Review of Latest Reports. Journal of Education, Health and Sport. 2025;83:61795. eISSN 2391-8306.
https://doi.org/10.12775/JEHS.2025.83.61795
https://apcz.umk.pl/JEHS/article/view/61795

The journal has had 40 points in Minister of Science and Higher Education of Poland parametric evaluation. Annex to the announcement of the Minister of Education and Science of 05.01.2024 No. 32318. Has a Journal's Unique Identifier: 201159. Scientific disciplines assigned: Physical culture sciences (Field of medical and health sciences); Health Sciences (Field of medical and health sciences).
Punkty Ministerialne 40 punktów. Załącznik do komunikatu Ministra Nauki i Szkolnictwa Wyższego z dnia 05.01.2024 Lp. 32318. Posiada Unikatowy Identyfikator Czasopisma: 201159. Przypisane dyscypliny naukowe: Nauki o kulturze fizycznej (Dziedzina nauk medycznych i nauk o zdrowiu); Nauki o zdrowiu (Dziedzina nauk medycznych i nauk o zdrowiu).
The authors declare that there is no conflict of interests regarding the publication of this paper.
Received: 01.06.2025. Revised: 30.06.2025. Accepted: 05.07.2025. Published: 08.07.2025.

Innovations in Pharmacotherapy of Diabetes: A Review of Latest Reports

Katarzyna Czechowska, Aleksandra Świerczewska, Piotr Komasara, Julka Nowakowska, Aleksandra Sędek, Lena Merchel, Ilona Bednarek, Sylwia Lach, Karol Błąd, Kinga Kałuża

Authors:

Katarzyna Czechowska [KC]

Provincial Combined Hospital in Kielce, ul. Grunwaldzka 45, 25-736 Kielce

email: katarzynaczechowska01@gmail.com

https://orcid.org/0009-0002-3637-5552

Aleksandra Świerczewska [AŚ]

Provincial Combined Hospital in Kielce, ul. Grunwaldzka 45, 25-736 Kielce

email: ola.swierczewska125@gmail.com

https://orcid.org/0009-0005-9882-5768

Piotr Komasara [PK]

Faculty of Medicine, Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland

email: sp.komasara@gmail.com

https://orcid.org/0009-0002-7964-8696

Julia Nowakowska [JN]

Faculty of Medicine, Jan Kochanowski University of Kielce, IX Wieków Kielc 19A, Kielce, Poland

email: julia.nowakowska260@gmail.com

https://orcid.org/0009-0002-4508-727X

Aleksandra Sędek [AS]

Provincial Combined Hospital in Kielce, ul. Grunwaldzka 45, 25-736 Kielce

email: aleks.sedek89@gmail.com

https://orcid.org/0009-0002-2841-0493

Lena Merchel [LM]

Independent Public Health Care Institution of the Ministry of Internal Affairs and Administration in Kielce, ul. Wojska Polskiego 51, 25-375 Kielce

Lenamerchel@op.pl

https://orcid.org/0009-0002-9582-6843

Ilona Bednarek [IB]

Provincial Specialist Hospital in Czerwona Góra

Czerwona Góra 10, 26-060 Chęciny

email: ilona2023@interia.pl

https://orcid.org/0009-0009-9657-4132

Sylwia Lach [SL]

Independent Public Health Care Institution of the Ministry of Internal Affairs and Administration in Kielce, ul. Wojska Polskiego 51, 25-375 Kielce

email: lachsylwia@interia.eu

https://orcid.org/0009-0002-9638-3749

Karol Seweryn Błąd [KSB]

Independent Public Health Care Institution of the Ministry of Internal Affairs and Administration in Kielce, ul. Wojska Polskiego 51, 25-375 Kielce

blad.karol.4@gmail.com

https://orcid.org/0009-0001-6599-3635

Kinga Kałuża [KK]

Provincial Specialist Hospital in Czerwona Góra

Czerwona Góra 10, 26-060 Chęciny

Email: kaluza.k.k.m@gmail.com

https://orcid.org/0009-0009-4249-1497

ABSTRACT

Introduction and purpose

Diabetes mellitus represents one of the most pressing global health challenges of the 21st century. As a chronic, lifelong condition, it affects millions worldwide and contributes significantly to morbidity and mortality by damaging vital organs like the eyes, kidneys, nerves, heart, and blood vessels. The two main types are type 1, an autoimmune condition leading to no insulin production, and type 2, which is more common and caused by insulin resistance and inadequate insulin levels. The global rise in diabetes, especially Type 2 is largely fueled by

increasing urbanization, changes in eating habits, physical inactivity, and an aging population. Diabetes impacts more than just blood sugar levels, leading to numerous complications that reduce quality of life and place a heavy strain on healthcare systems. Although treatment options have advanced and outcomes have improved, challenges such as unequal access to care, poor treatment adherence, and limited patient education continue to hinder effective management of the disease. The review aims to explore the latest studies, innovations, and emerging possibilities in diabetes treatment.

Material and methods

The review was based on research of articles published from 2019 to 2025 on the PubMed database using the following keywords: diabetes, diabetes mellitus, T1D, T2D, HbA1c, SGLT2 Inhibitors, GLP-1 Receptor Agonists, DPP-4 Inhibitors, Thiazolidinediones, Teplizumab, Stem cell. The analysis draws upon recent clinical trial findings, updated guidelines from major diabetes organizations, and expert opinions to offer a detailed overview of the current landscape and future directions in this critical field of medical research and clinical practice.

Results

SGLT2 inhibitors effectively manage blood sugar in type 2 diabetes, offering additional benefits like weight loss, improved heart function, and kidney protection. They also show promise in treating NAFLD/NASH. GLP-1 receptor agonists, like semaglutide, liraglutide, and tirzepatide, improve blood sugar control and offer benefits such as reducing cardiovascular risk, mortality, and kidney disease progression. Semaglutide could prevent over 1 million premature deaths, mainly from cardiovascular causes. Tirzepatide shows the greatest reductions in HbA1c and weight. DPP-4 inhibitors reduce risks of heart failure, heart attacks, and strokes, with sitagliptin and vildagliptin showing the most consistent benefits. However, saxagliptin may increase heart failure risk. Pioglitazone has shown benefits in managing PCOS symptoms, improving metabolic outcomes and triglyceride levels, while rosiglitazone has a smaller effect on hormone levels. Pioglitazone also offers a higher pregnancy rate in IVF treatments for women with PCOS compared to metformin. A combination of SGLT2 inhibitors and pioglitazone shows promise for MASH management in diabetic patients. In prostate cancer research, pioglitazone reduced cancer cell growth but didn't induce cell death, requiring further study. Teplizumab is the first FDA-approved disease-modifying immunotherapy for type 1 diabetes. It works by modifying T cells to protect pancreatic β-cells from autoimmune attack.

Teplizumab significantly improved C-peptide levels, indicating better insulin production improved and also insulin secretion during tests.

Conclusions

Recent literature highlights significant advancements in the pharmacotherapy of diabetes mellitus, encompassing both type 1 and type 2 disease. Key innovations include updates to clinical practice guidelines emphasizing personalized and proactive management strategies, the emergence of highly effective dual glucose-dependent insulinotropic polypeptide (GIP) and glucagon-like peptide-1 (GLP-1) receptor agonists, and the expanding role of sodium-glucose cotransporter-2 (SGLT2) inhibitors for cardio-renal protection. Furthermore, research continues to explore the potential of glucagon-like peptide-1 receptor agonists (GLP-1 RAs) in type 1 diabetes, alongside breakthroughs in immunotherapies like Teplizumab for delaying disease onset and the rapidly evolving field of stem cell therapy and islet cell transplantation aiming for a functional cure. These innovations collectively hold the potential to improve glycemic control, reduce the incidence of complications, and enhance the quality of life for individuals living with diabetes. Research into novel drug targets and therapeutic strategies, such as those aimed at addressing insulin resistance directly or modulating the gut microbiome, also holds great potential for future breakthroughs in diabetes care.

Keywords: diabetes, diabetes mellitus, T1D, T2D, HbA1c, SGLT2 Inhibitors, GLP-1 Receptor Agonists, DPP-4 Inhibitors, Thiazolidinediones, Teplizumab, Stem cells

INTRODUCTION

Diabetes is a group of metabolic disorders primarily defined by high blood sugar levels (hyperglycemia). Hyperglycemia in diabetes results from defects in insulin secretion, in action, or both. Over time, this chronic high blood sugar level can cause secondary damage and severely impair various organs, particularly the eyes, kidneys, nerves, heart, and blood vessels. Based on reports from the International Diabetes Federation, approximately 589 million people representing 11.1% of the adult population were living with diabetes in 2024 with projections to rise to 853 million by 2050. (2)

The core problem in diabetes is that insulin doesn't work effectively in the body's tissues, disrupting the metabolism of carbohydrates, fats, and proteins. The vast majority of diabetes cases fall into one of two distinct groups: diabetes type 1 and diabetes type 2. Type 1 diabetes

is caused by a complete lack of insulin due to autoimmune destruction of pancreatic cells and often appears in childhood or adolescence. Type 2 diabetes is far more common (80-90% of cases) and results from a combination of insulin resistance and insufficient insulin production to compensate. This type usually develops in adults, and its prevalence has increased significantly worldwide. Other types of diabetes such as maturity-onset diabetes of the young (MODY) can be caused by single gene mutation or environmental factors. (3)

Table 1. Criteria for detection of diabetes and intermediate hyperglycaemia

Diagnostic criterion	**WHO criteria**	**ADA criteria**
Diabetes		
Fasting plasma glucose (FPG)	≥7.0 mmol/L (126 mg/dL)	≥7.0 mmol/L (126 mg/dL)
2 h plasma glucose during OGGT	≥11.1 mmol/L (200 mg/dL)	≥11.1 mmol/L (200 mg/dL)
HbA1c	≥6.5% (48 mmol/mol)	≥6.5% (48 mmol/mol)
Impaired fasting glucose (IFG)		
Fasting plasma glucose (FPG)	6.1–6.9 mmol/L (110–125 mg/dL)	5.6–6.9 mmol/L (100–125 mg/dL)
Impaired glucose tolerance (IGT)		
2 h plasma glucose during OGGT	7.8–11.0 mmol/L (140–199 mg/dL)	7.8–11.0 mmol/L (140–199 mg/dL)
HbA1c	-	5.7%–6.4%

The ability to control Type 2 Diabetes Mellitus and prevent or delay its associated complications relies heavily on receiving an early diagnosis and appropriate treatment and support. The complexity of managing this disease necessitates continuous advancements in pharmacotherapy to achieve optimal patient outcomes and mitigate the risk of long-term complications, including cardiovascular disease, nephropathy, retinopathy, and neuropathy.

For example end-stage renal disease (ESRD), a condition necessitating hemodialysis, is most commonly caused by Type 2 diabetes mellitus when considering single diseases. Furthermore,

It's reported that diabetic nephropathy is present in approximately 40% of patients who need renal replacement therapy. (4)

The aim of this review is to provide a detailed overview of pharmacotherapy and the latest innovations in diabetes treatment and also impact extended benefits for the whole organism. The review is based on the latest articles from the PubMed database in the years 2019-2025. The analysis draws upon recent clinical trial findings, updated guidelines from major diabetes organizations, and expert opinions to offer a detailed overview of the current landscape and future directions in this critical field of medical research and clinical practice.

Keywords like diabetes, diabetes mellitus, T1D, T2D, HbA1c, SGLT2 Inhibitors, GLP-1 Receptor Agonists, DPP-4 Inhibitors, Thiazolidinediones, Teplizumab, Stem cells were used in the investigation.

TREATMENT OF DIABETES

Table 2. Comparison of the innovations in pharmacology treatment methods in diabetes

Therapy	Mechanism of action	Efficiency	Adverse events	References
SGLT2 Inhibitors	Inhibits the SGLT2 protein, which is responsible for the reabsorption of glucose from the tubular lumen	Significantly reduce blood glucose levels, reduce major cardiovascular risks, improve LVEF, increase bone markers, improve in albuminuria	Female genital mycotic infections, urinary tract infections, hypoglycemia	(5, 6, 7, 8, 9, 10)
GLP-1 Receptor Agonists	Incretin hormone, stimulate insulin secretion after an oral glucose load via the incretin effect	Significantly reduce blood glucose levels, reduce major cardiovascular risks and progression of kidney disease, good results in obesity treatment or overweight patients	Nausea, vomiting, diarrhea	(13, 14, 15, 16, 17, 18)
DPP-4 Inhibitors	Ubiquitous enzyme, increasing insulin secretion and decreasing glucagon secretion	Significantly reduce major cardiovascular risks	Low incidence of adverse events but the most frequent: upper respiratory tract infections, nasopharyngitis,	(19, 20, 21)

			headaches, urinary tract infections and arthralgia	
Thiazolidinediones	Regulate gene expression by binding to peroxisome proliferator-activated receptor-gamma (PPAR-gamma)	Help with glycemic control and insulin resistance; positive effect in PCOS-improvement metabolic markers	Edema and congestive heart failure, weight gain, increased risk of fractures and bladder cancer hepatotoxicity, increased ovulation	(22, 23, 24)
Teplizumab	Anti-CD3 monoclonal antibody	Significantly delay in T1D, lower OGTT glucose values, higher C-peptide levels, improve beta cell function and total and early insulin secretion	Lymphopenia, rash, leukopenia, headache	(30,31,32, 33)
Stem cell therapy - Lantidra	Multipotent stromal cells capable of self-renewal and differentiation into multiple cell lineages.	Impact on producing and secreting insulin	Nausea, anemia, fatigue, abdominal pain, diarrhea	(34, 35, 36)

SGLT2 Inhibitors

Sodium-Glucose Transport Protein 2 (SGLT2) inhibitors also known as flozines prevent glucose reabsorption in the proximal convoluted tubules of the kidneys, leading to its elimination from the body through the urine (glycosuria) and reduction blood glucose. (5)

As part of a treatment plan including diet and exercise, canagliflozin, dapagliflozin, empagliflozin, and ertugliflozin are FDA-approved for improving blood sugar levels in adult patients with type 2 diabetes. (5)

Medications like Empagliflozin, a highly selective SGLT2 inhibitor, reduce blood glucose levels by increasing the amount of glucose expelled in the urine. This mechanism is insulin-independent, offering the benefit of a lower risk of hypoglycemia. The osmotic diuretic effect associated with these drugs may also help patients lose weight. Normally, the kidneys reabsorb around 180g of glucose daily in the proximal tubules, but Empagliflozin can promote excretion of this about 80g. Research confirms that Empagliflozin successfully lowers fasting and after-

meal blood sugar and supports weight loss in diabetic patients, whether used as monotherapy or combined with other treatments. Its method of lowering blood sugar is distinct from that employed by traditional antidiabetic drugs (6).

Research that was investigating the impact of SGLT2 inhibitor - empagliflozin on glycemic markers and osteoporosis in patients with type 2 diabetes shows results after six months of treatment. Both groups showed improvements for glycemic parameters: fasting blood glucose (FBG), 2-hour postprandial blood glucose (2 h PG), glycosylated hemoglobin A1c (HbA1c) and bone markers: bone mineral density (BMD), serum phosphorus, serum calcium but the group that received empagliflozin achieved significantly greater reductions in glycemic parameters and significantly greater increases in bone markers compared to the control group ($P < 0.05$ for all comparative changes). Following 12 months, only a small percentage of patients in the intervention group experienced a fracture (2%, 1 out of 50), a rate considerably lower and statistically significant compared to the 16.33% observed in the control group (8 out of 49 patients) ($P = 0.036$) (6).

In a study by Albulushi et al., meta-analyses were carried out based on randomized controlled trials and observational studies to determine the effects of SGLT2 inhibitors on heart failure with preserved ejection fraction (HFpEF) in patients with type 2 diabetes (T2D). The study showed that, SGLT2 inhibitors significantly enhanced Left Ventricular Ejection Fraction (LVEF) with a 95% confidence interval (CI) of 2.0 to 4.4, $p < 0.001$; $I^2 = 25\%$, reduced myocardial fibrosis with 95% CI -4.2 to -2.8, $p < 0.001$ and improved functional capacity with 95% CI 35 to 65, $p < 0.001$. There were also positive impact on reductions in HbA1c 95% CI -1.3 to -0.7, $p < 0.001$, body weight 95% CI -2.6 to -1.4, $p < 0.001$ and lowering SBP 95% CI -6.0 to -3.6, $p < 0.001$ (7). In the analysis of efficacy and safety of tirzepatide, liraglutide, canagliflozin, ertugliflozin, empagliflozin, dapagliflozin, and henagliflozin compared with placebo we can see that canagliflozin 300 mg resulted in the greatest decrease in systolic blood pressure, with a mean difference of −5.96 mmHg (95% CI: −7.96 to −3.96 mmHg). What is more, canagliflozin 300 mg was also effective in weight reduction (78.4%) and HBA1c ([95% CI], -1.00% [-1.18, -0.82]) (18). Another study was investigating the impact between SGLT2 Inhibitors and cardiovascular outcomes Type 2 diabetes patients. The analysis showed significant advantages in reducing major cardiovascular risks by SGLT2 inhibitors. They substantially reduced the risk of cardiovascular death (RR = 0.59; 95% CI, 0.53–0.65), death from any cause (RR = 0.64; 95% CI, 0.60–0.68), and myocardial infarction (MI) (RR = 0.81; 95% CI, 0.76–0.87). SGLT2 inhibitors also significantly lowered the risk of hospitalization for

heart failure (HHF) by 23% (RR = 0.77; 95% CI, 0.74–0.80). Furthermore, the study demonstrated similar results about the effect of SGLT2i on the cardiovascular system among patients with both heart failure and diabetes (8).

The retrospective cohort study followed for a median of 1657 days analized kidney parameters of diabetes patients with lack of insulin that were treated with SGLT2 inhibitors. Results showed that compared to the control group, SGLT2 inhibitors significantly reduced the risk of both a 50% decline in eGFR to below 60 (HR 0.79, P < 0.001; 6.1% vs. 7.5%) and progression to eGFR <15 (HR 0.71, P = 0.015; 1.5% vs. 2.0%). What is more SGLT2i significantly reduced the rate of doubling serum creatinine (5.3% vs. 6.6%; HR 0.76, p < 0.001). Also notably, more SGLT2i users transitioned from micro- or macroalbuminuria to normoalbuminuria (51.0% vs. 44.2%; HR 0.83, p < 0.0001), including specifically from micro- to normoalbuminuria (59.2% vs. 41.8%; HR 0.74, p < 0.0001). Progression from micro- to macroalbuminuria was also less frequent with SGLT2i (23.1% vs. 28.7%; p < 0.0001) (9).

In two studies: by Chehrehgosha et. al., and by Monem et. al., they support the efficacy of SGLT2 inhibitors—dapagliflozin and empagliflozin—as effective alternatives to pioglitazone in the treatment of NAFLD/NASH, especially in patients with T2DM. These agents offer comparable or superior improvements in liver histology and fibrosis, and notably greater benefits in weight reduction, visceral fat loss, and quality of life. While histological outcomes were similar, SGLT2 inhibitors provided more favorable metabolic and anthropometric outcomes, particularly in non-diabetic and diabetic subgroups respectively. No serious safety concerns were reported in either study (27,28).

Research shows that SGLT2 inhibitors can note drug-related complications like genital mycotic infections and urinary tract infections, increased urination, hypoglycemia when used with sulfonylureas or insulin (5,11,12). However the main concern with SGLT2 inhibitor therapy is a significantly increased risk of diabetic ketoacidosis (DKA) particularly in patients with type 1 diabetes, despite the drugs offering other benefits like reduction in HbA1c and daily insulin dose, improved glucose control and weight loss. This risk limits their use in that patient population (9, 10, 11).

SGLT2 inhibitors definitely have demonstrated an expanding role in diabetes management that extends beyond glycemic control (6,7,8,9). However, there are some limitations in investigation, like research based on a small population (6). One of the studies was focused on short/medium-term effects, while the long-term impacts are not fully explained. Future research

should address this by conducting more high-quality, longer-term RCTs (7). In the other one there are variable duration of follow-up trials, and the fact that most studies are retrospective designs although high-quality (8).

GLP-1 Receptor Agonists

Glucagon-like peptide-1 (GLP1) agonists are incretin hormones that stimulate glucose-dependent insulin secretion which is insufficient in diabetes.

Recent clinical guidelines from the American Diabetes Association (ADA) recommend GLP-1 receptor agonists not only for glucose control but also for their benefits in reducing mortality, cardiovascular risk and slowing the progression of kidney disease. In a modelling study based on the SELECT trial of patients with atherosclerotic cardiovascular disease in the United States, projections suggest that administering semaglutide 2.4 mg to all eligible individuals could avert approximately 1,231,295 premature deaths, reflecting a 16% reduction in relative risk. Notably, an estimated 674,823 of these prevented deaths would be attributable to cardiovascular causes (15). In another, the retrospective cohort study of 27 279 participants with type 2 diabetes and advanced-stage chronic or end-stage kidney disease was observed that GLP-1 receptor agonists were linked to lower overall and infection-related death rates compared to DPP-4 inhibitors ([HR], 0.79; 95% CI, 0.63-0.98) (17). The results of Lin et al. cohort study of patients with advanced diabetic kidney disease with an eGFR < 30 mL/min per 1.73 m2 shows that GLP-1RAs were associated with fewer kidney events compared with DPP-4i (38.2% vs. 44.2%; HR 0.72, 95% CI 0.56–0.93), however cardiovascular event rates were similar between both groups (HR 0.88, 95% CI 0.68–1.13) (16). In a meta-analysis about GLP-1 receptor agonists used in patients with diabetes type 2, was found to reduce major cardiovascular events (MACE) by 14% (HR 0.86; 95% CI 0.80–0.93; $p<0.0001$), with consistent benefits across all subgroups analyzed. They also lowered all-cause mortality by 12%, hospitalizations for heart failure by 11%, and kidney-related outcomes by 21%, with no increased risk of serious side effects like hypoglycemia, retinopathy, or pancreatic issues (14).

Semaglutide, Liraglutide and Tirzepatide (dual GIP/GLP-1 receptor agonists) are FDA-approved for obesity treatment or for overweight patients with related health conditions. A total of 28 randomized controlled trials comprising 8,499 participants were included in the analysis of efficacy and safety of tirzepatide, liraglutide, canagliflozin, ertugliflozin, empagliflozin, dapagliflozin, and henagliflozin compared with placebo. The greatest reduction in HbA1c was observed with tirzepatide 15 mg ([95% CI], −2.24% [−2.52%, −1.96%]) followed by tirzepatide 10 mg (MD [95% CI], −1.99% [−2.29%, −1.69%]), tirzepatide 5 mg ([95% CI],

−1.82% [−2.11%, −1.53%]), and liraglutide 1.2 mg ([95% CI], −1.23% [−1.41%, −1.05%]). The weight reduction was also the most effective with tirzepatide 15mg ([95% CI], −8.74 kg [−9.83 kg, −7.66 kg]), followed by tirzepatide 10 mg ([95% CI], −7.13 kg [−8.40 kg, −5.86 kg]), tirzepatide 5 mg (MD [95% CI], -5.38 kg [-6.65, -4.11] kg). However, liraglutide 1.8mg showed the highest probability of causing adverse events (OR [95% CI], 2.57 [1.78, 3.70]). but with no significant differences in all treatment groups (18).

GLP-1 receptor agonists commonly cause nausea, vomiting, and diarrhea, which may lead to dehydration and, in some cases, acute kidney injury. Other side effects include dizziness, headaches, mild rapid heartbeat, and digestive discomfort. They also heighten satiety, so eating while full can trigger temporary nausea—best managed by slowly adjusting the dose. Injection-site irritation is frequent, especially with long-acting versions. Mild hypoglycemia may occur, but serious cases are uncommon. Overall, the treatment is well-tolerated, with only about 10% of users discontinuing due to side effects (13).

DPP- 4 inhibitors

DPP-4 inhibitors - oral diabetic drugs , called gliptins, are ubiquitous enzymes that inhibit degradation of incretin hormones - primarily GLP-1 and GIP, which help regulate blood glucose levels by increasing insulin release from pancreatic beta cells and decreasing glucagon secretion from pancreatic alpha cells (19).

A large meta-analysis of 27 studies with over 1.5 million participants found that, in type 2 diabetes patients taking metformin, adding a DPP-4 inhibitor significantly lowers the risk of major cardiovascular events and all-cause mortality compared to adding a sulfonylurea. This suggests DPP-4 inhibitors may offer superior cardiovascular protection and better long-term outcomes (20).

Another large-scale cohort study found that DPP-4 inhibitors are associated with significantly lower risks of major cardiovascular events, heart failure, heart attacks, and strokes compared to sulfonylureas. Sitagliptin (0.89 [0.85-0.94]) and vildagliptin ([0.77 [0.60-0.99]) offered the most consistent cardiovascular benefits, however saxagliptin may increase heart failure risk. These findings suggest a favorable cardioprotective profile for most DPP-4 inhibitors (21).

Thiazolidinediones

Thiazolidinediones (TZDs), such as rosiglitazone and pioglitazone, are insulin-sensitizing drugs used to manage type 2 diabetes. They improve blood sugar control without causing hypoglycemia and are safe for patients with kidney disease. TZDs work by activating PPAR-

gamma receptors, leading to enhanced glucose uptake, reduced liver glucose production, and increased adiponectin. (22).

In the research by Abdalla et. al., they evaluated the pioglitazone and rosiglitazone effects in managing PCOS symptoms. Polycystic ovary syndrome (PCOS) is a hormonal disorder in women of reproductive age, often linked to insulin resistance and an increased risk of type 2 diabetes. Results show that pioglitazone significantly lowered triglyceride levels and fasting insulin, indicating improved metabolic outcomes. Rosiglitazone, when compared to metformin, showed a marginal reduction in luteinising hormone (LH) levels. While thiazolidinediones (rosiglitazone, pioglitazone) may improve some hormonal and metabolic markers in PCOS, they tend to increase body weight and BMI. In contrast, metformin appears more favorable for weight-related outcomes, making it a potentially better option for weight-sensitive patients with PCOS (23).

Another randomized clinical trial investigated the effects of pioglitazone versus metformin on IVF outcomes in 172 women with polycystic ovary syndrome (PCOS)-related infertility. Participants were divided into two equal groups: one received 15 mg of pioglitazone and the other 1000 mg of metformin, both taken twice daily for six weeks before starting IVF treatment. Key outcomes included the number of oocytes retrieved, embryos formed, and confirmed pregnancies. The study found no significant differences in the number of eggs or embryos between the two groups, indicating that both treatments were similarly effective in stimulating ovulation and embryo development. However, a significantly higher pregnancy rate was observed in the pioglitazone group (48.8%) compared to the metformin group (32.6%), suggesting that pioglitazone may have a beneficial effect on endometrial receptivity or embryo implantation. In conclusion, while both medications had comparable effects on ovulation and embryo development, pioglitazone appeared to offer a clear advantage in terms of achieving pregnancy, making it a potentially more effective option for improving IVF outcomes in women with PCOS (24).

Pioglitazone was identified as the most effective Western medicine for treating nonalcoholic steatohepatitis (NASH), based on a network meta-analysis of 37 clinical trials. It significantly improved liver histology by resolving NASH without worsening fibrosis, boosted HDL cholesterol, and reduced nonalcoholic fatty liver disease, NAFLD activity scores. With a high SUCRA ranking of 91.4%, pioglitazone outperformed other medications in overall therapeutic benefit, making it a leading option for managing NASH, despite other drugs like Aldafermin offering superior liver enzyme improvements. (25)

Another study investigated the impact of combining SGLT2 inhibitors, pioglitazone, and GLP1 receptor agonists on MASH in patients with type 2 diabetes. In a real-world setting involving 888 patients followed for nearly 4 years, the combination of these drugs—especially SGLT2i with pioglitazone—was significantly associated with reduced FAST scores, indicating improvement in liver health. The findings suggest that dual therapy, particularly SGLT2i plus pioglitazone, may offer a promising strategy for managing MASH in diabetic patients.(26)
In the study by Atas et. al., it is showed that pioglitazone, a PPARγ agonist, significantly reduced proliferation in both primary and metastatic prostate cancer (PCa) cells without inducing apoptosis. It decreased cell viability, metabolic activity, and DNA content in a dose- and time-dependent manner. However, additional detailed and long-term studies will be necessary to thoroughly understand the effects of these metabolic inhibitors on PCa development, progression, and patient survival (29).

Innovations in Type 1 Diabetes Pharmacotherapy: Immunotherapy - Teplizumab

Teplizumab, humanized Fc receptor non binding anti-CD3 monoclonal antibody represents a groundbreaking advancement as the first FDA-approved disease-modifying therapy for use in adults and children over eight years in type 1 diabetes. This immunotherapy drug works by modifying T cells and suppressing autoreactive immune responses that inappropriately target pancreatic β-cells mainly by boosting anti-inflammatory cytokines (IL-4, IL-10) which protect them from destruction (30).

The randomized, placebo controlled trial that enrolled 328 children and adolescents with recently diagnosed type 1 diabetes shows the impact of Teplizumab on endogenous insulin production indicated by C-peptide levels. At week 78, Teplizumab treatment resulted in C-peptide levels compared to placebo, representing a 59.3% difference favoring Teplizumab. Baseline C-peptide was 0.13 pmol/mL higher ($P<0.001$) than in placebo. Furthermore, at week 78, 94.9% of patients in the Teplizumab group maintained a peak C-peptide level of 0.2 pmol/mL or greater, a rate substantially higher than the 79.2% seen in the placebo group. The beneficial effect of Teplizumab on C-peptide was consistent across patient subgroups (31).

In a randomized controlled trial of participants with high-risk of developing diabetes and then in extended follow-up of that report we can see results about metabolic parameters and delay in progression to diabetes. Clinical trials have demonstrated that a single 14-day course of Teplizumab can effectively delay the progression to stage 3 (symptomatic) type 1 diabetes in individuals aged 8 years and older who are diagnosed with stage 2 (presymptomatic) disease

(33). 50% patients treated with teplizumab was diagnosed with diabetes type 1 and had a median time to diagnosis that disease of 59.6 months, significantly extending the time compared to the 27.1 months observed in the placebo group where 78% participants developed diabetes, respectively (HR=0.457, p=0.01) (33). What is more, Teplizumab treatment led to a significantly greater increase in insulin secretion during the test compared to placebo ($p = 0.01$, $p = 0.0004$). During the first hour of the OGTT ($p = 0.007$) as well as during the second hour ($p = 0.03$) insulin secretion was improved versus decline in the placebo group which indicated improvement in beta cell function (33).

Research shows that Teplizumab also notes drug-related complications in more than 10% of the treatment group like: lymphopenia (73%), rash (36%), leukopenia (21%) and headache (11%). Cytokine release syndrome (CRS) is reaction that reveals with fever, nausea, fatigue, headache, myalgia, arthralgia, elevated ALT, AST and bilirubin levels in early beginning of treatment (first five days) 5% of patients vs. 0,8% in the placebo group. Key safety protocols administering giving patients premedication and observing for signs of CRS. Also teplizumab therapy must be permanently stopped if the level of enzymes (ALT and AST) is five times higher than normal (32).

Innovations in Type 1 Diabetes Pharmacotherapy: Stem cell therapy

Lantidra has become the first FDA-approved cellular therapy for adults with type 1 diabetes who experience frequent, severe hypoglycemia and are unable to maintain target HbA1c levels despite intensive treatment. This innovative therapy uses pancreatic islet cells from deceased donors, delivered through a single infusion into the hepatic portal vein. Immunosuppressive medications are also necessary to maintain the survival and function of the transplanted islet cells. Once transplanted, the donor beta cells begin producing insulin, potentially reducing or even eliminating the patient's reliance on insulin injections. Approval was based on two nonrandomized, single-arm studies involving 30 patients with type 1 diabetes and hypoglycemia unawareness. Among them, 21 participants (70%) remained insulin-free for at least one year, 12 (40%) for one to five years, and 9 (30%) for over five years, highlighting Lantidra’s potential to offer long-term insulin independence for a subset of patients. Lantidra’s side effects varied by patient but commonly included nausea, fatigue, and abdominal issues. Serious complications, often related to the infusion process or required immunosuppressants, were frequent and sometimes led to loss of islet function and a return to insulin use because of

stopping immunosuppressive therapy. These risks must be balanced against potential benefits on a case-by-case basis (35, 36).

CONCLUSIONS

The latest data analysis from 2019-2025 have shown that targeted drugs like SGLT2 inhibitors, GLP-1 receptor agonists, DPP-4 inhibitors and Thiazolidinediones offer the most significant pharmacological benefits. Recent updates in diabetes pharmacotherapy emphasize the fast-paced progress in drug development, medical technologies, and clinical treatment strategies. Breakthroughs such as the emergence of powerful dual GIP/GLP-1 receptor agonists and the growing use of SGLT2 inhibitors are reshaping the treatment landscape for type 2 diabetes, providing better blood sugar regulation along with notable cardiovascular and kidney health benefits. GLP-1 analogs are typically regarded as more effective in reducing blood glucose levels and enhancing glycemic control; however, they are also associated with a higher incidence of adverse effects, such as nausea, diarrhea, and other gastrointestinal symptoms. In contrast, DPP-4 inhibitors are considered to have a more favorable safety profile, though their glucose-lowering efficacy may be comparatively modest. Thiazolidinediones may also benefit conditions like polycystic ovarian syndrome and nonalcoholic steatohepatitis. Potential additional effects include anti-inflammatory and anti-cancer properties, although further research is needed to confirm these benefits. For type 1 diabetes, the approval of Teplizumab marks a new era in disease modification, while progress in stem cell therapy and islet cell transplantation offers the potential for a functional cure. As a result, there is a growing need for more intensive research efforts today.

Disclosures

Author's contribution:

Conceptualization: KC, AŚ, IB; Methodology: PK, IB, JN, AS; Software: KC, AŚ, IB; Check: PK, JN, SL, AS; Formal analysis: KC, KSB, KK; Investigation: AŚ, IB, SL; Resources: JN, KSB, KC; Data curation: KC, JN, KSB, AS**;** Writing -rough preparation: KC; Writing -review and editing: PK, LM, KK**;** Visualization: KC, LM, KK**;** Supervision: LM, KSB; Project administration: SL, KC, AŚ

Founding Statement: The study did not receive external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Not applicable.

Conflict of Interest Statement: The authors declare no conflicts of interest.

All authors have read and agreed with the published version of the manuscript.

Declaration of the use of generative AI and AI-assisted technologies in the writing process. In preparing this work, the authors used ChatGPT for the purpose of improving language and readability. After using this tool the authors have reviewed and edited the content as needed and accept full responsibility for the substantive content of the publication.

REFERENCES

1. Janić M, Janež A, El-Tanani M, Maggio V, Rizzo M. Diabetes: Recent Advances and Future Perspectives. Biomedicines. 2024 Dec 18;12(12):2875. doi: 10.3390/biomedicines12122875. PMID: 39767781; PMCID: PMC11673822.

2. International Diabetes Federation. IDF Diabetes Atlas, 11th edn. Brussels, Belgium: 2025. Available at: https://diabetesatlas.org

3. Fliegerová KO, Mahayri TM, Sechovcová H, Mekadim C, Mrázek J, Jarošíková R, Dubský M and Fejfarová V (2025) Diabetes and gut microbiome. *Front. Microbiol*. 15:1451054. doi: 10.3389/fmicb.2024.1451054

4. Müller M, Schönfeld CL, Grammer T, Krane V, Drechsler C, Genser B, Kohnen T, Wanner C, März W. Risk factors for retinopathy in hemodialysis patients with type 2 diabetes mellitus. Sci Rep. 2020 Aug 25;10(1):14158. doi: 10.1038/s41598-020-70998-9. PMID: 32843669; PMCID: PMC7447637.

5. Padda IS, Mahtani AU, Parmar M. Sodium-Glucose Transport Protein 2 (SGLT2) Inhibitors. [Updated 2023 Jun 3]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2025 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK576405/

6. Tan J, Guo A, Zhang K, Jiang Y, Liu H. The effect of empagliflozin (sodium-glucose cotransporter-2 inhibitor) on osteoporosis and glycemic parameters in patients with type 2 diabetes: a quasi-experimental study. BMC Musculoskelet Disord. 2024 Oct 7;25(1):793. doi: 10.1186/s12891-024-07900-5. PMID: 39375646; PMCID: PMC11460138.

7. Albulushi A, Tanoh DB, Almustafa A, Al Matrooshi N, Zolty R, Lowes B. Comparative effects of glucagon-like peptide-1 receptor agonists and sodium-glucose co-transporter-2

inhibitors on heart failure with preserved ejection fraction in diabetic patients: a meta-analysis. Cardiovasc Diabetol. 2024 Aug 31;23(1):324. doi: 10.1186/s12933-024-02415-8. PMID: 39217337; PMCID: PMC11366143.

8. Zhou Z, Zheng M, Zuo Z, Wu T. Comparison of cardiovascular outcomes of new antihyperglycemic agents in Type 2 Diabetes Mellitus: a meta-analysis. ESC Heart Fail. 2024 Jun;11(3):1647-1656. doi: 10.1002/ehf2.14726. Epub 2024 Feb 28. PMID: 38419382; PMCID: PMC11098653.

9. Tsur A, Cahn A, Hanoch L, Pollack R. Kidney outcomes with SGLT2 inhibitors in patients with diabetes and an insulin-deficient phenotype: A real world analysis. Diabetes Obes Metab. 2025 Jun;27(6):3176-3184. doi: 10.1111/dom.16329. Epub 2025 Mar 14. PMID: 40084557; PMCID: PMC12046457.

10. Danne T, Garg S, Peters AL, Buse JB, Mathieu C, Pettus JH, Alexander CM, Battelino T, Ampudia-Blasco FJ, Bode BW, Cariou B, Close KL, Dandona P, Dutta S, Ferrannini E, Fourlanos S, Grunberger G, Heller SR, Henry RR, Kurian MJ, Kushner JA, Oron T, Parkin CG, Pieber TR, Rodbard HW, Schatz D, Skyler JS, Tamborlane WV, Yokote K, Phillip M. International Consensus on Risk Management of Diabetic Ketoacidosis in Patients With Type 1 Diabetes Treated With Sodium-Glucose Cotransporter (SGLT) Inhibitors. Diabetes Care. 2019 Jun;42(6):1147-1154. doi: 10.2337/dc18-2316. Epub 2019 Feb 6. PMID: 30728224; PMCID: PMC6973545.

11. Sizar O, Podder V, Talati R. Empagliflozin. [Updated 2023 May 29]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2025 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK532925/

12. Horii T, Oikawa Y, Kunisada N, Shimada A, Atsuda K. Real-world risk of hypoglycemia-related hospitalization in Japanese patients with type 2 diabetes using SGLT2 inhibitors: a nationwide cohort study. BMJ Open Diabetes Res Care. 2020 Nov;8(2):e001856. doi: 10.1136/bmjdrc-2020-001856. PMID: 33246930; PMCID: PMC7703042.

13. Collins L, Costello RA. Glucagon-Like Peptide-1 Receptor Agonists. [Updated 2024 Feb 29]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2025 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK551568/

14. Sattar N, Lee MMY, Kristensen SL, Branch KRH, Del Prato S, Khurmi NS, Lam CSP, Lopes RD, McMurray JJV, Pratley RE, Rosenstock J, Gerstein HC. Cardiovascular, mortality, and kidney outcomes with GLP-1 receptor agonists in patients with type 2 diabetes: a systematic review and meta-analysis of randomised trials. Lancet Diabetes Endocrinol. 2021

Oct;9(10):653-662. doi: 10.1016/S2213-8587(21)00203-5. Epub 2021 Aug 20. PMID: 34425083.

15. Nanna MG, Doan QV, Fabricatore A, Faurby M, Henry AD, Houshmand-Oeregaard A, Levine A, Navar AM, Scassellati Sforzolini T, Toliver JC. Population-level impact of semaglutide 2.4 mg in patients with obesity or overweight and cardiovascular disease: A modelling study based on the SELECT trial. Diabetes Obes Metab. 2025 Jun;27(6):3442-3452. doi: 10.1111/dom.16370. Epub 2025 Apr 4. PMID: 40183412; PMCID: PMC12046440.

16. Lin Y, Wang TH, Tsai ML, Wu VC, Tseng CJ, Lin MS, Li YR, Chang CH, Chou TS, Tsai TH, Yang NI, Hung MJ, Chen TH. The cardiovascular and renal effects of glucagon-like peptide 1 receptor agonists in patients with advanced diabetic kidney disease. Cardiovasc Diabetol. 2023 Mar 17;22(1):60. doi: 10.1186/s12933-023-01793-9. PMID: 36932379; PMCID: PMC10024371.

17. Chen JJ, Wu CY, Jenq CC, Lee TH, Tsai CY, Tu HT, Huang YT, Yen CL, Yen TH, Chen YC, Tian YC, Yang CW, Yang HY. Association of Glucagon-Like Peptide-1 Receptor Agonist vs Dipeptidyl Peptidase-4 Inhibitor Use With Mortality Among Patients With Type 2 Diabetes and Advanced Chronic Kidney Disease. JAMA Netw Open. 2022 Mar 1;5(3):e221169. doi: 10.1001/jamanetworkopen.2022.1169. PMID: 35254430; PMCID: PMC8902651.

18. Teng Y, Fan X, Yu R, Yang X. Evaluation and comparison of efficacy and safety of tirzepatide, liraglutide and SGLT2i in patients with type 2 diabetes mellitus: a network meta-analysis. BMC Endocr Disord. 2024 Dec 24;24(1):278. doi: 10.1186/s12902-024-01805-z. PMID: 39719583; PMCID: PMC11668020.

19. Kasina SVSK, Baradhi KM. Dipeptidyl Peptidase IV (DPP IV) Inhibitors. [Updated 2023 May 22]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2025 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK542331/

20. Hasan R, Chugaeva UY, Mohammadian M, Zamanifard S, Mohammadian-Hafshejani A. Cardiovascular and mortality outcomes of DPP-4 inhibitors vs. sulfonylureas as metformin add-on therapy in patients with type 2 diabetes: A systematic review and meta-analysis. PLoS One. 2025 May 5;20(5):e0321032. doi: 10.1371/journal.pone.0321032. PMID: 40323973; PMCID: PMC12083876.

21. Wang J, Wu HY, Chien KL. Cardioprotective effects of dipeptidyl peptidase-4 inhibitors versus sulfonylureas in addition to metformin: A nationwide cohort study of patients with type 2 diabetes. Diabetes Metab. 2022 May;48(3):101299. doi: 10.1016/j.diabet.2021.101299. Epub 2021 Oct 30. PMID: 34728339.

22. Eggleton JS, Jialal I. Thiazolidinediones. [Updated 2023 Feb 20]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2025 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK551656/

23. Abdalla MA, Shah N, Deshmukh H, Sahebkar A, Östlundh L, Al-Rifai RH, Atkin SL, Sathyapalan T. The Effect of Thiazolidinediones in Polycystic Ovary Syndrome: A Systematic Review and Meta-Analysis of Randomised Controlled Trials. Adv Ther. 2024 Jun;41(6):2168-2195. doi: 10.1007/s12325-024-02848-3. Epub 2024 Apr 29. PMID: 38683294.

24. Taheripanah R, Kazemi SN, Taheripanah A, Fereidoonjah S. A randomized controlled trial comparing pioglitazone and metformin prior to in vitro fertilization in polycystic ovary syndrome - associated infertile women: impact on pregnancy rates. Ann Med Surg (Lond). 2024 Feb 28;86(5):2696-2701. doi: 10.1097/MS9.0000000000001816. PMID: 38694345; PMCID: PMC11060239.

25. Shi R, Chai K, Wang H, Zhou J, Yang S, Li J, Qiao C, Sheng X, Zhang X, Wu J. Clinical Assessment of Common Medications for Nonalcoholic Fatty Liver Disease: A Systematic Review and Bayesian Network Meta-Analysis. J Evid Based Med. 2025 Mar;18(1):e70002. doi: 10.1111/jebm.70002. PMID: 39963857; PMCID: PMC11833758.

26. Lee CH, Lui DT, Mak LY, Fong CH, Chan KS, Mak JH, Cheung CY, Chow WS, Woo YC, Yuen MF, Seto WK, Lam KS. Benefits of combining SGLT2 inhibitors and pioglitazone on risk of MASH in type 2 diabetes-A real-world study. Diabetes Obes Metab. 2025 Feb;27(2):574-582. doi: 10.1111/dom.16049. Epub 2024 Nov 5. PMID: 39497579.

27. Abdel Monem MS, Adel A, Abbassi MM, Abdelaziz DH, Hassany M, Raziky ME, Sabry NA. Efficacy and safety of dapagliflozin compared to pioglitazone in diabetic and non-diabetic patients with non-alcoholic steatohepatitis: A randomized clinical trial. Clin Res Hepatol Gastroenterol. 2025 Mar;49(3):102543. doi: 10.1016/j.clinre.2025.102543. Epub 2025 Jan 29. PMID: 39884573.

28. Chehrehgosha H, Sohrabi MR, Ismail-Beigi F, Malek M, Reza Babaei M, Zamani F, Ajdarkosh H, Khoonsari M, Fallah AE, Khamseh ME. Empagliflozin Improves Liver Steatosis and Fibrosis in Patients with Non-Alcoholic Fatty Liver Disease and Type 2 Diabetes: A Randomized, Double-Blind, Placebo-Controlled Clinical Trial. Diabetes Ther. 2021 Mar;12(3):843-861. doi: 10.1007/s13300-021-01011-3. Epub 2021 Feb 14. PMID: 33586120; PMCID: PMC7882235.

29. Atas E, Berchtold K, Schlederer M, Prodinger S, Sternberg F, Pucci P, Steel C, Matthews JD, James ER, Philippe C, Trachtová K, Moazzami AA, Artamonova N, Melchior F, Redmer T, Timelthaler G, Pohl EE, Turner SD, Heidegger I, Krueger M, Resch U, Kenner L.

The anti-diabetic PPARγ agonist Pioglitazone inhibits cell proliferation and induces metabolic reprogramming in prostate cancer. Mol Cancer. 2025 May 5;24(1):134. doi: 10.1186/s12943-025-02320-y. PMID: 40320521; PMCID: PMC12051277.

30. Jeun R. Immunotherapies for prevention and treatment of type 1 diabetes. Immunotherapy. 2025 Feb;17(3):201-210. doi: 10.1080/1750743X.2025.2473311. Epub 2025 Mar 4. PMID: 40033931; PMCID: PMC11951698.

31. Ramos EL, Dayan CM, Chatenoud L, Sumnik Z, Simmons KM, Szypowska A, Gitelman SE, Knecht LA, Niemoeller E, Tian W, Herold KC; PROTECT Study Investigators. Teplizumab and β-Cell Function in Newly Diagnosed Type 1 Diabetes. N Engl J Med. 2023 Dec 7;389(23):2151-2161. doi: 10.1056/NEJMoa2308743. Epub 2023 Oct 18. PMID: 37861217.

32. Saleem MR, Khan MT. Teplizumab: a promising intervention for delaying type 1 diabetes progression. Front Endocrinol (Lausanne). 2025 Apr 28;16:1533748. doi: 10.3389/fendo.2025.1533748. PMID: 40357199; PMCID: PMC12066327.

33. Sims EK, Bundy BN, Stier K, Serti E, Lim N, Long SA, Geyer SM, Moran A, Greenbaum CJ, Evans-Molina C, Herold KC; Type 1 Diabetes TrialNet Study Group. Teplizumab improves and stabilizes beta cell function in antibody-positive high-risk individuals. Sci Transl Med. 2021 Mar 3;13(583):eabc8980. doi: 10.1126/scitranslmed.abc8980. PMID: 33658358; PMCID: PMC8610022.

34. Bagno LL, Salerno AG, Balkan W, Hare JM. Mechanism of Action of Mesenchymal Stem Cells (MSCs): impact of delivery method. Expert Opin Biol Ther. 2022 Apr;22(4):449-463. doi: 10.1080/14712598.2022.2016695. Epub 2021 Dec 27. PMID: 34882517; PMCID: PMC8934282.

35. Food and Drug Administration (FDA) News Release. FDA approves first cellular therapy to treat patients with type 1 diabetes. Jun 28, 2023. Available at:https://www.fda.gov/news-events/press-announcements/fda-approves-first-cellular-therapy-treat-patients-type-1-diabetes#.

36. Parums DV. Editorial: First Regulatory Approval for Allogeneic Pancreatic Islet Beta Cell Infusion for Adult Patients with Type 1 Diabetes Mellitus. Med Sci Monit. 2023 Aug 1;29:e941918. doi: 10.12659/MSM.941918. PMID: 37525584; PMCID: PMC10403990.