

Molecular Mechanisms by which GLP-1 RA and DPP-4i Induce Insulin Sensitivity

Running Title: GLP-1RA and Insulin Resistance

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Abstract

Glucagon-like peptide-1 is a peptide of incretin family which is used in the management of diabetes as glucagon-like peptide-1 receptor agonist (GLP-1RA). Dipeptidyl peptidase-4 enzyme metabolizes glucagon-like peptide-1 and various dipeptidyl peptidase-4 enzyme inhibitors (DPP-4i) are also used in the management of diabetes. These antidiabetic agents provide anti-hyperglycemic effects via several molecular mechanisms including promoting insulin secretion, suppression of glucagon secretion and slowing the gastric emptying. There is some research suggesting that they can induce insulin sensitivity in peripheral tissues. In this study, we review the possible molecular mechanisms by which GLP-1RA and DPP-4i can improve insulin resistance and increase insulin sensitivity in insulin-dependent peripheral tissues.

Keywords: Glucagon-like peptide-1, Glucagon-like peptide-1 receptor agonist, dipeptidyl peptidase-4 inhibitors, Oxidative Stress, GLUT-4, Diabetes Mellitus.

Introduction

The incidence of diabetes mellitus (DM) is increasing worldwide in an epidemic proportion [1]. This chronic disorder affects several metabolic pathways resulting in the production of various toxic byproducts leading to various complications of diabetes [2-4]. DM acts as a potent upstream event for many pathophysiologic pathways including oxidative stress, inflammation, fibrosis, apoptotic processes, TLR (toll-like receptor) activation, necrotic events and the activity of death receptors thereby inducing various forms of tissue dysfunction and diabetic complications [4-6]. Inadequate response to circulatory insulin, which is known as insulin resistance, play significant roles in the onset and progress of these pathologic pathways [7-9]. Therefore, different classes of antidiabetic medicines have been developed to increase the tissue sensitivity to insulin and normalize the glycemia thereby preventing the pathophysiologic mechanisms involved in diabetic complications [10-12].

Glucagon-like peptide receptor-1 agonists (GLP-1RA) is one of the classes of antidiabetic medications which provide anti-hyperglycemic effects via several molecular mechanisms [13]. These pharmacologic agents exert their pleiotropic effects by lowering postprandial hyperglycemia mainly via binding to their specific receptors in various tissues [13]. They have a lower risk of hypoglycemia due to their glucose-dependent mode of action [14, 15]. Dipeptidyl peptidase-4 inhibitors (DPP-4i) are another group of antidiabetic agents which work by inhibition of GLP-1 breakdown thereby increasing its bioavailability [13]. There is some evidence suggesting that they also can increase insulin sensitivity in insulin-dependent peripheral tissues [16-18]. In the current review, we present the possible molecular mechanisms by which GLP-1RA modulate insulin sensitivity in patients with diabetes. It must be noted that higher levels of GLP-1 modulate glucose homeostasis by several mechanisms including slowing gastric emptying, inhibiting gluconeogenesis and suppression of appetite [19, 20]. In this review, we focus on its insulin-sensitizing effects.

Classification of Diabetes Mellitus

Type 1 (T1DM) and type 2 diabetes (T2DM) are the two common forms of diabetes [21]. (T1DM accounts for about 5-10% of all patients with diabetes and mainly results from beta-cell dysfunction, reduction in insulin release and lower circulatory levels of insulin [21]. Type 2 diabetes (T2DM) is the most prevalent form of diabetes which account for more than 90% of patients with diabetes [21]. T2DM mainly results from an inadequate cellular response to insulin (insulin resistance) in insulin-dependent peripheral tissues in addition of beta-cell dysfunction and other pathophysiological defects [21]. Gestational diabetes is another type of DM which occurs in pregnant women likely due to hormonal variations during pregnancy period and insulin resistance [22]. Other forms of diabetes are latent autoimmune diabetes in adults or LADA, maturity-onset diabetes of the young (MODY), secondary diabetes to various conditions such as pancreatitis and secondary to various medications such as corticosteroids [23].

Glucose Homeostasis and Insulin Signaling

Glucose is a hexose carbohydrate and the preferred metabolic substrate for many types of human cells. It is a hydrophilic molecule with a molecular weight of 180 and thereby, is too big for easily passing across the cellular membrane [24, 25]. The two major pathways for glucose to enter cells are via active transporters (by sodium-glucose cotransporters or SGLTs) or via specific carriers (by glucose transporters or GLUT) [25]. GLUTs are a family of proteins that provide bidirectional facilitated glucose transport across the cell membrane without consuming energy and are based on the glucose concentration gradient across the cell membrane [25, 26]. These are at least 14 different GLUT proteins in human of which GLUT1-4 are more important in glucose homeostasis [25, 27]. GLUT-4 works completely dependent on insulin hormone [25, 28]. It remains in the cytoplasmic vesicles in non-active forms and

activates in response to insulin and translocate into the specific cell membrane and thereby facilitates glucose entering into the adipocytes, cardiac and skeletal muscle cells [25, 27]. Since striated muscle tissues act as a storage for glucose as glycogen, GLUT-4 plays an important role in the whole-body glucose homeostasis [27].

Insulin is an important metabolic hormone made up of 51 amino acids and has a molecular weight of 5808D. It belongs to a family of peptides which includes insulin-like growth factors (IGF) I and II, relaxin and some other insulin-like peptides [29, 30]. It has two distinct chains known as α and β . These chains are linked together by two disulfide bridges and a third one which is within the α chain [29, 30]. Insulin is secreted by pancreatic beta-cells when glucose enters into the islets via specific glucose carriers known as GLUT-2 by facilitated diffusion in responses to various stimuli such as higher plasma levels of glucose and amino acids [29, 30].

Glucose is phosphorylated to G6P (glucose-6-phosphate) within the beta-cells [31]. This process is catalyzed by the glucokinase enzyme activity which acts as "glucose sensor" into the islets and thereby controls the rate of glucose entering into the islets and in turn the rate of insulin release [31]. G6P increases the ATP (adenosine triphosphate) to ADP (adenosine diphosphate) ratio in the beta-cells which in turns closes the ATP-sensitive K^+ channels, depolarizes beta-cell membrane and augments the intracellular calcium levels by opening the voltage-dependent Ca^{2+} channels in the pancreatic beta-cells [31]. Increasing the intracellular Ca^{2+} levels induces the exocytosis of secretory granules containing insulin/proinsulin molecules from the beta-cells into the circulation [31].

Insulin facilitates the glucose entering into the adipocytes, cardiac and skeletal muscle cells by sequential steps known as insulin signal transduction (IST) [32]. IST is initiated by binding the insulin to the α chain of specific receptors known as insulin receptors (IRs). IR is a member of transmembrane tyrosine kinases composed of α and β which is activated by insulin as well as

by IGF¹ 1 and 2 [32]. This process induces structural changes in β chain domain by prompting the auto-phosphorylation of tyrosine residues followed by downstream events such as the recruitment of different adaptor proteins i.e. insulin receptor substrates (IRSs), Shc² protein, and APS protein³ [25, 33]. These processes provide an appropriate binding site for the IRS-1⁴ [33]. IRS-1 can be also activated by other kinases including ERK1/2⁵, atypical PKC⁶, S6K1⁷, SIK2⁸, AKT, mTOR⁹ and ROCK1¹⁰ as well as other types of kinases such as AMPK¹¹ and GSK3¹² [33, 34]. Activated IRS-1 binds to PI3K¹³ and activate it which in turn catalyzes the conversion of PIP₂¹⁴ to PIP₃¹⁵ [35]. PIP₃ is itself a potent activator for PKB (protein kinase B also known as Akt) [35]. Akt is final effector in this pathway which facilitates glucose entering into the cells by localization of GLUT-4 and inhibiting the glycogen synthase kinase leading to more glycogen synthesis [30, 35]. The complicated process of IST and insulin sensitivity can be modulated in all the above steps [36-38].

GLP-1 Receptor Agonists and DPP-4 Inhibitors

The glucagon-like peptide (GLP) is a protein belonging to the incretin family which is secreted from the intestine in response to food ingestion and stimulates the GLP-1 receptor (GLP-1R) [39]. The GLP-1R is a G-protein coupled protein mainly found in the pancreatic beta-cells and is involved in regulating the blood glucose in several ways [40]. It composed of two domains,

¹ Insulin-like growth factor

² SHC-transforming

³ adapter protein with a PH and SH2 domain

⁴ insulin receptor substrate type 1

⁵ extracellular signal-regulated kinase 1/2

⁶ protein kinase C

⁷ Ribosomal protein S6 kinase beta-1

⁸ serine/threonine-protein kinase 2

⁹ mammalian target of rapamycin

¹⁰ Rho-associated protein kinase 1

¹¹ AMP-activated protein kinase

¹² Glycogen synthase kinase 3

¹³ phosphoinositide 3-kinase

¹⁴ Phosphatidylinositol 4,5-bisphosphate

¹⁵ Phosphatidylinositol 3,4,5-trisphosphate

the extracellular domain binds the C-terminal helix of GLP-1 and the transmembrane domain binds to the N-terminal region of GLP-1 [41-44].

GLP-1 RA is a family of antidiabetic agents that mimic the effects of incretin hormone [45-47]. Incretin is a family of metabolic hormones including GLP-1 and GIP (gastric inhibitory peptide), which decrease postprandial blood glucose by inhibition of glucagon secretion from pancreatic α -cells and inducing insulin release from β -cell in a blood glucose-dependent manner [46, 48, 49]. GLP-1RA have additional effects such as delaying the gastric emptying, appetite suppression, declining nutrient absorption in the gut, improvement of lipid metabolism, inhibition of pancreatic β -cell apoptosis and induction of beta-cell neogenesis [48, 50, 51].

Table 1. Two main classes of antidiabetic drugs which work by GLP-1 level

Classes of Antidiabetic Drug	Approved Forms	Mechanisms of Hypoglycemic Effects	Ref.
GLP-1RA	Exenatide, Albiglutide, Liraglutide, Lixisenatide, Semaglutide, Dulaglutide	Mimic the hypoglycemic effects of incretin such as insulin secretion, glucagon release suppression, appetite inhibition, slowing the gastric emptying	[46, 47]
DPP-4i	Sitagliptin, Saxagliptin, Vildagliptin, Linagliptin	Block the GLP-1 deactivator enzyme (DPP-4 enzyme) leading to enhanced hypoglycemic effects of native GLP-1	[52, 53]

Dipeptidyl peptidase-4 inhibitor (DPP-4i) are another type of antidiabetic agents with similar hypoglycemic effects to GLP-1RA. They act by preventing the inactivation of GLP-1 thereby increasing the active levels of native GLP-1 [52, 53]. After posttranslational processes of pre-glucagon (PG) peptides in intestinal L cells, at least four separate forms of PG produced that are all can be inactivated by DPP-4 enzyme by removing the two amino acids from N-terminal residue [54]. DPP-4 is mainly located on the surface of the most types of cells including the

endothelial cells, renal epithelial cells and T lymphoid cells, where they have a binding partner element which makes intracellular signals [55].

GLP-1 and Insulin Sensitivity

In addition to the aforementioned hypoglycemic effects, there is strong evidence indicating GLP-1 increases insulin sensitivity in peripheral tissues [17, 19] (fig 1). The higher levels of GLP-1, by either GLP-1RA and/or DPP-4i administration, can induce peripheral insulin sensitivity through several direct or indirect molecular pathways [17, 18, 56]. In the following paragraphs, we discuss the possible molecular mechanisms involved in the GLP-1 dependent insulin sensitivity.

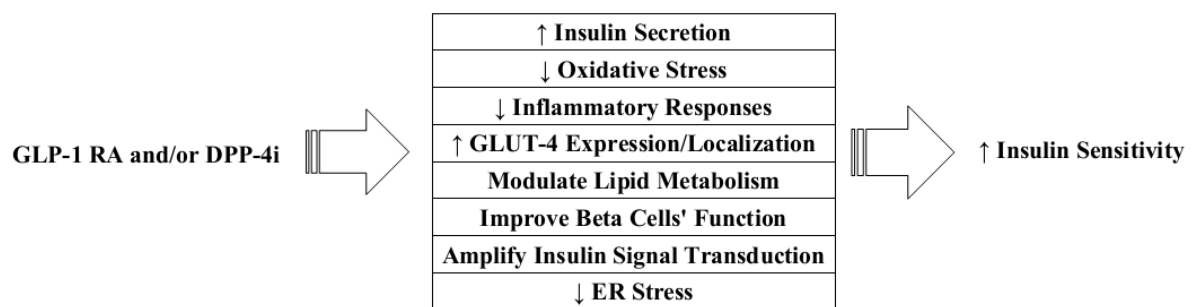


Figure 1: Possible molecular mechanisms by which GLP-1 induces insulin sensitivity

1. GLP-1 and Insulin Secretion

GLP-1 receptors analogues and/or its breakdown enzyme inhibitors are known stimulators for pancreatic beta cells to secrete postprandial insulin in response to higher levels of blood glucose in a concentration-dependent manner [57]. It has suggested that GLP-1 induces insulin secretion through several molecular pathways such as cAMP production, Ca²⁺ dependent voltage-gated channels, proinsulin granule recruitment and promoting vesicle docking [57]. There is also evidence that DPP-4i can stimulate insulin release [58]. Consequently, GLP-1 based therapies are now routinely used in clinical practice for the treatment of T2DM and

obesity [57, 59, 60]. This islet cell stimulating effect of GLP-1 could be one of the therapeutic targets even in some cases of T1DM and/or T2DM with dysfunctional beta-cells [57, 61, 62].

2. GLP-1 and Oxidative Stress

Oxidative stress has pivotal roles in the pathophysiology of many complications of diabetes as well as insulin resistance [63-65]. The free radical overload reduces the insulin sensitivity and induces insulin resistance by several molecular pathways including IKK β ¹⁶/NF- κ B¹⁷ and JNK¹⁸ pathways, IRS degradation, GLUT-4 down-regulation, lowering the insulin-dependent IRS-1 and PIP-kinase transfer between cytoplasm and microsomes [65-68]. Hence, readjusting the redox state in favor of physiologic milieu with a balance between free radicals and antioxidative elements is an attractive goal for designing novel antidiabetic agents [11, 69, 70].

On the other hand, emerging evidence suggests that GLP-1 receptor induction by either GLP-1RA and /r DPP-4i can result in improved antioxidative outcomes [39, 71, 72]. Oh and colleagues in 2017 suggested that GLP-1 have antioxidative potentials either by the glucose-lowering effects or via Nrf2¹⁹ signaling pathways and potentiation of antioxidant defense system [39, 73]. The inducers of Nrf2 signaling pathways improves insulin sensitivity in diabetic milieu [74, 75]. Deng and coworkers in 2018 showed that GLP-1 can induce Nrf2 signaling pathways and increases the expression of antioxidant elements in the neuronal cells [73]. Fernández-Millán and coworkers in 2016 found that GLP-1 directly increases Nrf2 signaling and improves oxidative stress in the pancreatic beta-cells [76]. Also, Puddu et al in 2013 provided further data suggesting GLP-1 attenuated the oxidative stress by suppressing AGE²⁰-RAGE²¹ interaction in the diabetic milieu [77]. Moreover, Tomas et al in 2011

¹⁶ inhibitor of nuclear factor kappa-B kinase subunit beta

¹⁷ nuclear factor kappa-B

¹⁸ c-Jun N-terminal kinase

¹⁹ Nuclear factor erythroid 2-related factor 2

²⁰ Advanced glycation end product

²¹ Receptors for AGE

discovered a nano-peptide derived from GLP-1 which reduces the oxidative stress via mitochondria-dependent mechanism [78]. Patel et al in 2013 demonstrated that GLP-1 improves insulin sensitivity by attenuating the oxidative stress in diabetic mice [79]. Okada et al in 2014 and Rizzo et al in 2015 provided clinical evidence indicating liraglutide decreased the oxidative stress in patients with T2DM [80, 81]. This evidence strongly suggested that GLP-1 can induce insulin sensitivity by ameliorating oxidative stress [77-81].

3. GLP-1 and Inflammatory responses

Inflammatory processes have pivotal roles in the pathophysiology of insulin resistance [65, 82]. These biologic events can impair IST via several molecular mechanisms including IKK β /NF- κ B and JNK²² pathway activation, serine phosphorylation of IRS-1 in the site of 307, GLUT-4 and IRS-1 down-regulation as well as IRS-1 degradation [65, 83-85]. Hence, ameliorating the inflammation is one of the ideal therapeutic targets for antidiabetic medicines [10, 12]. There is strong evidence indicating GLP-1 has potent anti-inflammatory potentials which may be beneficial against inflammatory responses and reduces the circulating inflammatory mediators leading to an increase in peripheral insulin sensitivity [12, 86-91]. Koderá et al in 2011 demonstrated that exendin-4, of the GLP-1RA, directly reduced inflammatory mediators such as ICAM (intercellular adhesion molecule-1), type IV collagen, and Nf- κ b activation as well as reduced macrophage infiltration [91]. Also, Shiraki and coworkers in 2012 reported that GLP-1 attenuated inflammatory responses via lowering the TNF- α and Nf- κ b expression levels in the umbilical endothelial cells [90]. Krasner et al in 2014 reported similar findings implying GLP-1 reduces inflammatory responses by calcium and AMPK dependent molecular pathways [87].

²² c-Jun N-terminal kinase

Guo and colleagues in 2016 found that exendin-4 improved insulin sensitivity by lowering the inflammatory responses [17]. They demonstrated that it markedly reduced macrophage-derived insulin resistance by Nf- κ b dependent molecular pathway leading to lower inflammation-induced insulin resistance [17]. Also, Zheng et al in 2018 revealed that raising the levels of GLP-1 by DPP-4i improved insulin sensitivity by ameliorating the inflammatory responses via AMPK/mTOR molecular mechanisms in the diabetic animals [92]. Zhuge and coworkers in 2016 provided data indicating linagliptin improved insulin sensitivity by modulating macrophage-dependent inflammatory events [93]. These evidence suggest that GLP-1 can promote insulin sensitivity by a reduction in inflammatory responses [17, 92, 93].

4. GLUT-4 Expression and Glucose Transport

The GLUT-4 is insulin-dependent glucose carrier and any disruption of its function will result in insulin resistance [94, 95]. There is some evidence that GLP-1 induces glucose transport across the cell membrane [96-98] and also induce GLUT-4 expression [99, 100]. Wang et al in 1997 demonstrated that GLP-1 increases GLUT-4 expression and glucose transport in adipocytes [100]. Villanueva-Peñacarrillo et al in 2001 reported that GLP-1 up-regulated the GLUT-4 expression at both mRNA and protein levels in adipocytes and muscle tissues of diabetic animals [99]. Also, Green and coworkers in 2012 observed that GLP-1 increased the GLUT-4 expression at the protein level by PI3-K dependent mechanism in human satellite cells [101]. Moreover, Andreozzi and coworkers in 2016 found that GLP-1 increased glucose transport across skeletal muscle cells via up-regulating the GLUT-4 by an AMPK-dependent manner [102]. Similarly, Li et al in 2014 demonstrated that liraglutide induces GLUT-4 translocation/expression by AMPK dependent mechanisms in skeletal muscles of diabetic mice [103]. Giannocco et al in 2013 provided similar data for DPP-4i indicating sitagliptin increased GLUT-4 translocation in the heart and skeletal muscle of rats [104]. This evidence strongly

suggests that GLP-1 can improve insulin sensitivity by GLUT-4 expression/translocation [101-104].

5. GLP-1 and Plasma Lipids' Profile

The plasma lipid profile affects insulin sensitivity [105, 106]. Emerging evidence has demonstrated the molecular relationships between lipid profile and dysfunctional lipid metabolism with varying degrees of insulin resistance indicating an optimum profile of plasma lipid is needed for physiological insulin sensitivity in peripheral tissues [106]. Higher levels of adipocytes and lipids/lipoproteins (e.g. cholesterol, triglycerides, HDL, VLDL and LDL), initiate molecular mechanisms that have a negative effect on insulin sensitivity [106-109].

GLP-1 can potentially modulate lipid metabolism and correct dyslipidemia through various molecular mechanisms and through activating different mediators and metabolic enzymes [110-112]. They can potentially modulate some microRNAs (miR) involved in lipid metabolism such as miR-200b, miR-200c, miR-34a, miR-338 and miR-21 [113-116]. Therefore, recent evidence suggested these hypoglycemic medications are promising therapeutic agents for dyslipidemia-induced disorders such as NAFLD (non-alcoholic fatty liver disease) and atherosclerosis in the diabetic milieu [117-120]. Ejarque et al in 2019 demonstrated that GLP-1 expressed on adipocytes regulates the adipose tissue metabolism leading to higher insulin sensitivity [121]. Also, Parlevliet and coworkers in 2012 found that GLP-1 receptor agonist, exendin-4, improved insulin sensitivity by regulating the VLDL production in diabetic mice [122]. Moreover, Cani et al in 2006 suggested that lipid-lowering and insulin-sensitizing effects of oligofructose are mediated via GLP-1 receptors in mice with T1DM [123]. There is a similar finding of the role of DPP-4i [124-126]. Baumeier et al in 2017 reported that higher expression levels of DPP-4i improved insulin sensitivity by readjusting the lipid metabolism [124]. Also, Silva and colleagues in 2019 showed that DPP-4i activity is correlated to the improvement of lipid metabolism and an increase in insulin sensitivity in

patients with T2DM [125]. This evidence strongly suggested that GLP-1 can improve insulin sensitivity by controlling lipid metabolism and thereby improving dyslipidemia, however, more clinical studies are still needed.

6. GLP-1 and Insulin Signaling Pathways

The GLP-1 amplifies IST in various steps [127]. Wang et al in 1997 demonstrated that GLP-1 analogues improved insulin signaling in 3T3-L1 adipocytes [100]. Gao et al in 2007 provided evidence suggesting GLP-1 induce insulin signaling pathways by up-regulation of phosphorylated IR- β , IRS-1, Akt and GSK-3 β (glycogen synthase kinase 3 beta) in adipocytes leading to more insulin sensitivity [127]. Kawamori and coworkers in 2017 reported that GLP-1 signaling compensated IST impairment in the diabetic milieu and improved it [128]. They found that GLP-1 promoted Akt phosphorylation and protein expression of cyclins A, D1 and E leading to improved IST in adipocytes [128]. This evidence strongly suggested that GLP-1 has potent effects on insulin signaling pathways and thereby induces insulin sensitivity at least partly via IST induction [100, 127, 128].

7. GLP-1 and Beta-cell Function

A healthy beta- cell with normal physiologic function is a key element for appropriate insulin sensitivity [129, 130]. Many cases of DM are related to varying degrees of beta-cell dysfunction and thereby, reversing the pathophysiologic pathways involved in beta-cell dysfunction is an attractive target for the management of diabetes [131, 132]. There is some evidence indicating that GLP-1 can improve beta-cell function [133-136]. Tews et al in 2009 demonstrated that exendin-4 prevents beta-cell apoptosis and improves islets' function in a diabetic milieu [133]. Kawamori et al in 2017 showed that GLP-1 signaling induced beta-cell proliferation in adipocytes [128]. Caporarello and coworkers in 2017 reported that GLP-1 receptor agonists markedly enhanced pancreatic beta-cell generation in mice [137]. Also, Kim and colleagues in 2017 reported the same findings implying exendin-4 ameliorates beta-cell

damage and improves insulin sensitivity in rats [134]. Moreover, Shimoda et al in 2011 found that liraglutide promoted pancreatic beta-cell function in diabetic mice [135]. Gedulin et al in 2005 reported that exendin-4 increases insulin sensitivity index and reduces blood glucose levels by increasing beta-cell mass in obese rats [136]. They showed that GLP-1 has trophic effects on pancreatic islets and exerts neogenesis and cell proliferation independent of glucose homeostasis and body weight [136, 138]. Other possible pathways are also suggested [139, 140]. Hao et al in 2017 demonstrated that GLP-1 increases insulin sensitivity by improvement in beta-cell function through PDX-1²³/JAK signaling pathways [139]. Also, Zummo and coworkers in 2017 found that GLP-1 protects pancreatic beta-cell function by readjusting the autophagy/lysosomal homeostasis in INS-1E β -cells [140]. Akarte and colleagues in 2012 showed that DPP-4i (vidagliptin) increases beta-cell mass in the diabetic milieu [141]. This evidence suggest that improvement in beta-cell function is another pathway by which GLP-1 induces insulin sensitivity [133-136] [139].

8. GLP-1 and ER Stress

Endoplasmic reticulum (ER) is one of the main organelles in eukaryotic cells which have significant roles in the cellular homeostasis [142]. Various pathophysiological states and pharmacologic agents disturb the functioning of ER resulting in ER stress. ER stress contributes to the development of diabetes complications [143, 144]. There is some evidence suggesting GLP-1 can potentially improve ER stress in diabetic milieu [18, 135, 145]. Jiang et al in 2018 demonstrated that GLP-1 improved insulin sensitivity by ameliorating ER stress through mTOR signaling dependent pathways and its downstream mechanisms in adipocytes [18]. Also, Shimoda et al in 2011 reported that liraglutide improved ER stress-induced insulin resistance in the diabetic mice [135]. Moreover, Shimizu et al in 2012 found that vildagliptin (DPP-4i) improved ER stress in beta-cells by down-regulating the C/EBPB protein (a

²³ duodenal homeobox-1

transcription factor) in diabetic mice [145]. This evidence suggest that GLP-1 can modulate ER stress-induced insulin resistance [18, 135, 145].

Table 2. Possible insulin sensitizer influences of GLP-1 (Nrf2= Nuclear factor erythroid 2-related factor 2; HO-1= heme oxigenase-1; AGE= Advanced glycation end product; RAGE= receptor for AGE; Nf- κ b=nuclear factor kappa b; IRS-1=insulin receptor substrate-1; ER=endoplasmic reticulum; mTOR=mammalian target of rapamycin; C/EBPB= a transcription factor)

Molecular Mechanisms	Effects	Ref.
Insulin Secretion	Induces insulin expression/release via vary molecular mechanisms such as cAMP production, Ca ²⁺ dependent voltage-gated channels, proinsulin granule recruitment and promoting vesicle ducking	[57, 59, 60]
Oxidative Stress	Attenuates oxidative stress by several molecular pathways such as Nrf2, HO-1 and AGE-RAGE interactions, reduces the free radical generation	[39, 73, 77-81]
Inflammatory Responses	Ameliorates inflammation-induced insulin resistance via lowering the pro-inflammatory mediators as Nf- κ b, ICAM-1, TNF- α and signaling pathways such as AMPK/mTOR	[17, 92, 93]
GLUT-4 Expression/Localization	Increase GLUT-4 expression/localization in insulin-dependent tissues	[101-104]
Lipid Metabolism	Improve plasma lipid profile leading to a lower rate of dyslipidemia-induced insulin resistance	[121, 123-126]
Beta-cell Function	Improve pancreatic beta-cell function via several molecular pathways as neogenesis induction and apoptosis inhibition	[133-136]
Insulin Signal Transduction	Amplify insulin signal transduction at various steps such as Akt and IRS-1 phosphorylation	[100, 127, 128]
ER Stress	Attenuate ER stress thru mTOR signaling or down-regulating the C/EBPB protein and thereby decline ER stress-induced insulin resistance	[18, 135, 145]

Other potential molecular pathways

In addition to the above described molecular pathways, some other molecular mechanisms may be involved in GLP-1 dependent insulin sensitivity [88][146]. GLP-1 potentially suppress

glucagon secretion which can lead to higher insulin sensitivity [146, 147]. Also, there is evidence suggesting GLP-1 can stimulate the expression and release of adipokines and adiponectin which have major roles in the insulin signaling pathways [88]. They can also potentially modulate the mitochondrial function and improves insulin resistance due to mitochondrial dysfunctions [148].

Conclusion

GLP-1 is one of the main peptides of the incretin family which modulates glucose homeostasis through several molecular pathways. The two GLP-1 pathways based therapies for the treatment of T2DM are GLP-1 receptor agonists and DPP-4 inhibitors. They act as anti-hyperglycemic agents through a variety of mechanisms including glucose dependent stimulation of insulin secretion, suppression of glucagon secretion, reduction of hepatic glucose output and suppression of appetite. These agents also increase insulin sensitivity via at least eight molecular pathways including oxidative stress, inflammation, ER stress, lipid metabolism, GLUT-4 expression/translocation, beta-cell function and insulin signaling pathways.

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Conflict of Interests

The authors declare that they have no conflict of interest in this study.

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