Glucagon-like peptide-1 improves insulin and proinsulin binding on RINm5F cells and human monocytes

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Glucagon-like peptide-1 improves insulin and proinsulin binding on RINm5F cells and human monocytes. Am J Physiol Endocrinol Metab 279: E88–E94, 2000.—Glucagon-like peptide-1(7–36)amide (GLP-1) is a potent incretin hormone secreted from distal gut. It stimulates basal and glucose-induced insulin secretion and proinsulin gene expression. The present study tested the hypothesis that GLP-1 may modulate insulin receptor binding. RINm5F rat insulinoma cells were incubated with GLP1.(0.01–100 nM) for different periods (1 min-24 h). Insulin receptor binding was assessed by competitive ligand binding studies. In addition, we investigated the effect of GLP-1 on insulin receptor binding on monocytes isolated from type 1 and type 2 diabetes patients and healthy volunteers. In RINm5F cells, GLP-1 increased the capacity and affinity of insulin binding in a time- and concentration-dependent manner. The GLP-1 receptor agonist exendin-4 showed similar effects, whereas the receptor antagonist exendin-(9–39)amide inhibited the GLP-1-induced increase in insulin receptor binding. The GLP-1 effect was potentiated by the adenyl cyclase activator forskolin and the stable cAMP analog Sp-5,6-dichloro-1-(N,N,N)-tetraacetic acid-AM. Glucagon, gastric inhibitory peptide (GIP), and GIP-(1–30) did not affect insulin binding. In isolated monocytes, 24 h incubation with 100 nM GLP-1 significantly (P < 0.05) increased the diminished number of high-capacity/low-affinity insulin binding sites per cell in type 1 diabetics (9,000 ± 2,300 vs. 18,500 ± 3,600) and in type 2 diabetics (15,700 ± 2,100 vs. 26,200 ± 4,200). Based on our previous experiments in IEC-6 cells and IM-9 lymphoblasts indicating that the low-affinity/high-capacity insulin binding sites may be more specific for proinsulin binding, we tested the hypothesis that GLP-1 may specifically modulate insulin receptor binding in RINm5F cells and monocytes. In both cell types, GLP-1 induced a significant increase in proinsulin binding. We conclude that, in RINm5F cells and in isolated human monocytes, GLP-1 specifically increases the number of high-capacity insulin binding sites that may be functional proinsulin receptors.
preliminary findings in RINm5F insulinoma cells (23). The present study extended these experiments and investigated the effects of GLP-1 agonistic and antagonistic peptides and structurally related gastrointestinal hormones. We further addressed the question whether GLP-1 may also modulate insulin receptors in other cell types and determined insulin receptor binding in monocytes isolated from healthy subjects and diabetic patients. Finally, additional experiments are provided, showing that GLP-1 increases the binding of proinsulin but not insulin-like growth factor I (IGF-I).

MATERIALS AND METHODS

Reagents. GLP-1-(7–36) amide, GLP-1-(7–37), exendin-4, exendin-(9–39) amide, GIP-(1–42), truncated porcine GIP-(1–30), forskolin, and human recombinant IGF-I were obtained from Saxon (Hannover, Germany). Human biosynthetic insulin, proinsulin, and glucagon were from Lilly (Indianapolis, IN), Sp-5,6-dichloro-1-β-d-ribofuransosyl-benzimidazole-3′,5′-monophosphorothioate (cBMPs) was from Biolog (Bremen, Germany), and 1.2-bis(0-aminophenoxy)ethane-N,N,N′,N′-tetraacetic acid (BAPTA)-AM was from Calbiochem (Bad Soden/Taunus, Germany). Human biosynthetic [125I]Tyr-A14 proinsulin (specific activity 360 μCi/μg) was labeled and HPLC was purified by A. Liebe (Hoechst, Frankfurt, Germany). Human recombinant [125I]Tyr-A14 proinsulin (specific activity 233 μCi/μg) was labeled by the lactoperoxidase method and subsequently purified by HPLC, as described previously (24). [125I]IGF-I (specific activity 250 μCi/μg) was purchased from Amersham (Braunschweig, Germany). [125I]GLP-1-(7–36) amide was labeled using the chloramine T method and was purified by HPLC as described (17). The binding assay buffer consisted of 50 mmol/l HEPES, 10 mmol/l dextrose, 15 mmol/l sodium acetate, 5 mmol/l KCl, 120 mmol/l NaCl, 1.2 mmol/l MgSO4, 10 mmol/l CaCl2, and 0.1% BSA, pH 7.8 adjusted with NaOH. All chemicals were purchased from Merck (Darmstadt, Germany) and were supplemented with 25 mM HEPES assay buffer. All other reagents were solved in HEPES assay buffer at a final concentration of 107 mononuclear cells/ml. Viability as assessed by trypan blue exclusion was always >95%.

Receptor binding studies. Freshly isolated monocytes were incubated for 24 h with indicated concentrations of GLP-1 in binding assay buffer at 37°C. The cell suspension was washed twice and adjusted to a cell number of 106 cells/ml in binding assay buffer. The binding assays with RINm5F cells were performed with confluent cell monolayers grown to a density of 1.5 × 105/well. Both cell types were incubated in assay buffer and solvent with GLP-1 or other agents or solvent alone for the indicated time periods. After removing the incubation buffer and washing the cells two times, specific binding of insulin, proinsulin, IGF-I, and GLP-1 was determined from competitive binding studies as previously described (21). Briefly, cells were incubated in assay buffer with 10 pM of [125I]-labeled peptides and various concentrations (10 pM-1 μM) of unlabeled homologous peptides for 2 h at 15°C. Cell bound and free intact activities were measured in an automatic gamma counter with 70% efficiency. Degradation of labeled peptides was determined by measuring the ability of intact tracer peptides to precipitate in ice-cold 5% TCA. The percentage of degraded tracer was determined after centrifugation (2,000 g force, 10 min) from the increase in TCA-soluble radioactivity over that observed in control wells containing buffer but no cells. [125I]-labeled insulin, proinsulin, and IGF-I were >98% precipitable before and >90% precipitable at the end of each experiment. [125I]-GLP-1 was >97% precipitable before and >85% precipitable at the end of each experiment. Specific [125I] peptide binding was determined by subtracting the amount of radioactivity bound nonspecifically in the presence of 1 μM unlabeled homologous peptide. All binding data were corrected for nonspecific binding and tracer degradation. Peptide binding capacity (% specific tracer binding) and affinity (IC50 values indicating half-maximal tracer displacement) were calculated from computer-assisted competition-inhibition curves. The number of binding sites per cell and dissociation constant (Kd) values of binding affinity were estimated by computer-assisted Scatchard analysis (21, 24, 42).

RESULTS

Binding of GLP-1 and related peptides on insulin binding in RINm5F cells. RINm5F cells displayed specific binding of 125I-GLP-1-(7–36)-amide (4.6%/106 cells; n = 3) that was competed by unlabeled GLP-1 with high affinity (IC50: 0.2 nM; Kd: 0.3 nM). Using the same tracer in freshly isolated monocytes of two healthy subjects, only weak binding of 125I-GLP-1-(7–36)-amide could be measured (0.44 ± 0.11%/106 cells) without displacement by unlabeled GLP-1 given from 10 pM to 1 μM. Increasing the number of monocytes up to 4 × 107 cells or performing the binding studies at 4°C did not change the negative results.

Effect of GLP-1 and related peptides on insulin binding in RINm5F cells. As shown in Fig. 1, GLP-1-(7–36) amide induced a time-dependent increase of specific insulin binding with significant effects already after 5 min. A twofold higher insulin binding was observed after 24 h incubation without further increases by
longer incubation periods (up to 72 h). GLP-1 yielded a
dose-dependent stimulation of insulin binding, with
half-maximal effects at 0.1 nM given for 24 h (Fig. 2).
We next investigated whether structurally or effect-
related hormones may also modulate insulin receptor
binding. RINm5F cells were incubated for 2 h with 1
nM of GLP-1 alone or in combination with the GLP-1
receptor agonist exendin-4 or the GLP-1 receptor an-
tagont exendin-(9–39) amide (8, 17). GLP-1-(7–36)
amide alone increased insulin binding from 100% (con-
trol) to 142 ± 6.3% (n = 17). Similar effects were
observed with GLP-(7–37), which increased insulin
binding to 141.7 ± 18.4% (n = 3). Incubation with
exendin-4 (1 nM) alone stimulated insulin binding
from 100% (control) to 161 ± 6% (P < 0.001; n = 6). The
GLP-1 antagonist exendin-(9–39) amide alone showed
no significant effects (116 ± 8%; n = 6). The GLP-1-
induced increase in insulin binding (150 ± 10%) could
be effectively blocked by 100 nM of exendin-(9–39)
amide (116 ± 9%, P < 0.05 vs. GLP-1 alone; n = 6). As
shown in Fig. 3, the dose-dependent increase in insulin
binding observed with GLP-1-(7–36) amide was not
seen with glucagon, GIP, or GIP-(1–30).
Mechanism of GLP-1-induced increase of insulin
binding in RINm5F cells.
Competitive binding data
revealed that GLP-1 increased 125I-insulin binding due
to an increased receptor binding affinity and capacity.
Figure 4 demonstrates a marked left shift of the com-
petition-inhibition curves after 24 h incubation with
GLP-1, indicating the improved binding affinity (IC50:
0.12 vs. 1.5 nM; Kd: 1.2 vs. 3.2 nM; GLP-1 vs. control,
P < 0.05). As shown by Scatchard analysis (Fig. 5), the
total number of insulin receptors concomitantly in-

![Fig. 1. Time dependency of the effect of 1 nM glucagon-like peptide
(GLP)-1 on specific 125I-labeled insulin binding in RINm5F cells.
Specific 125I-insulin binding was determined from competitive bind-
ing studies by subtracting the amount of radioactivity bound non-
specifically in the presence of 1 μM unlabeled insulin, which was
<3%. All binding data were corrected for nonspecific binding and tracer degradation. Data are means ± SE of 3 independent experi-
ments. *P < 0.05 and **P < 0.005.](http://ajpendo.physiology.org/)

![Fig. 2. Dose dependency of the GLP-1 effect on specific 125I-insulin
binding in RINm5F cells. Cells were incubated for 12 h with different
concentrations of GLP-1. Specific 125I-insulin binding was deter-
mined as described in MATERIALS AND METHODS and Fig. 1. Data are
means ± SE of 6 independent experiments. *P < 0.05 and **P <
0.01.](http://ajpendo.physiology.org/)

![Fig. 3. Effects of GLP-1 and related peptides on 125I-insulin binding
in RINm5F cells. Cells were incubated for 2 h with 1 and 100 nM of
GLP-1, glucagon, GIP, and GIP-(1–30). Specific 125I-insulin binding
was determined from competitive binding studies as described in
MATERIALS AND METHODS. Mean values ± SE of 6–17 separate exper-
iments are shown. ***P < 0.001.](http://ajpendo.physiology.org/)

![Fig. 4. Competition-inhibition curves of 125I-insulin binding to
RINm5F cells incubated with 1 nM GLP-1 or solvent for 24 h. Cells
were incubated with 10 pM of 125I-insulin and various concentrations
(10 pM-1 μM) of unlabeled insulin in assay buffer for 2 h at 15°C.
GLP-1 induced a marked increase in insulin binding affinity. Data
are means ± SE of 3 independent experiments. *P < 0.05, **P <
0.01, and ***P < 0.001.](http://ajpendo.physiology.org/)
GLP-1 improves insulin receptor binding

Effect of GLP-1 on insulin binding in RINm5F cells

In the presence of elevated glucose levels, the peptide potently augments insulin secretion. Insulin production is increased by a direct effect on proinsulin gene transcription, and glucose-insensitive β-cells are rendered responsive by the peptide. GLP-1 regulates function and number of its own receptors on β-cells. Other hormones, e.g., somatostatin and leptin, have been shown to inhibit the effects of GLP-1. The present study demonstrates for the first time that GLP-1 improves insulin and proinsulin binding in insulinoma cells and in monocytes isolated from healthy and diabetic subjects. In RINm5F cells, GLP-1 exerts time- and dose-dependent effects, with 30% of the maximum already at concentrations of 20–50 pM, which are found in humans under physiological conditions (37). GLP-1 significantly increased both capacity and affinity of insulin binding. The stimulatory effect of GLP-1 on insulin binding occurred even within minutes. This suggests that GLP-1 may act on insulin receptors mainly located within or near the cell membrane rather than stimulating receptor de novo synthesis.

Fig. 5. Scatchard analysis of 125I-insulin binding in RINm5F cells incubated with 1 nM GLP-1 or solvent for 24 h. Binding data from Fig. 4 were analyzed according to Scatchard analysis using a computer-assisted curve-fitting program. Two classes of binding sites were obtained after incubation with GLP-1, with a significant (P < 0.05) increase in the number of low-affinity/high-capacity sites. Mean values ± SE of 3 separate experiments are shown.

Fig. 6. Effect of GLP-1 on specific 125I-proinsulin binding in RINm5F cells. Specific 125I-proinsulin binding was determined by subtracting the amount of radioactivity bound nonspecifically in the presence of 1 μM unlabeled proinsulin. Cells were preincubated with different concentrations of GLP-1 for different periods. Binding data were corrected for nonspecific binding and tracer degradation. Data are means ± SE of 3 independent experiments. *P < 0.01 and **P < 0.001.
Table 1. Effect of GLP-1 on number and affinity of insulin receptors on monocytes isolated from healthy subjects, type 1 diabetics, and type 2 diabetics

<table>
<thead>
<tr>
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<th>High-Affinity/Low-Capacity Sites</th>
<th>Low-Affinity/High-Capacity Sites</th>
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<tbody>
<tr>
<td></td>
<td>No. of sites</td>
<td>$K_a$ pM</td>
</tr>
<tr>
<td>Control</td>
<td>953 ± 273</td>
<td>81 ± 47</td>
</tr>
<tr>
<td>Type 1 diabetics</td>
<td>919 ± 281</td>
<td>111 ± 41</td>
</tr>
<tr>
<td>Type 2 diabetics</td>
<td>840 ± 367</td>
<td>74 ± 35</td>
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</table>

Data are means ± SE; $n = 4$ subjects in each group. GLP, glucagon-like peptide; $\sim$, without; $\sim$, with; $K_a$, dissociation constant. By Scatchard analysis, high-affinity/low-capacity binding sites could be distinguished from low-affinity/high-capacity sites. $^p < 0.05$, diabetes vs. control. $^P < 0.05$, GLP-1 vs. +GLP-1.

From the changes in the shape of the Scatchard plots, it appeared that GLP-1 may lead to a conformational change of the insulin receptor that may be responsible for the improved binding affinity and capacity (5, 29, 47). GLP-1 increased the number of low-affinity/high-capacity sites, which in terms of their biological role are still a matter of debate (e.g., sparing receptors, insulin receptors mediating the mitogenic effects of insulin (5), binding sites for proinsulin/C peptide (20, 24)]. GLP-1 also induced a significant increase in proinsulin binding. This is in accordance with our previous findings in IM-9 lymphoblasts (24) and the small intestinal crypt cell line IEC-6 (20), indicating that the low-affinity/high-capacity insulin binding sites are receptors for proinsulin. In isolated pancreatic islets of normal hamsters, proinsulin was shown to be more potent than insulin to decrease insulin secretion (7). In epidemiological studies, elevated proinsulin levels have been correlated with $\beta$-cell injury, obesity, type 2 diabetes, and cardiovascular mortality (13, 25). Although the role of proinsulin in atherogenesis is not clear, in should be noted that proinsulin stimulates the synthesis of plasminogen-activator inhibitor type 1 from vascular endothelial cells with higher potency than insulin (43). Therefore, it would make sense that GLP-1 increases not only insulin but also proinsulin binding on $\beta$-cells to prevent proinsulin secretion in the postprandial state. This hypothesis needs to be confirmed in further studies, e.g., by revealing the molecular structure and biological relevance of the proinsulin receptor and using pancreatic $\beta$-cell-specific knock out of the insulin receptor (27).

The increase in insulin binding capacity was specific for GLP-1 and was not found for the related peptides GIP or glucagon. Exendin-4, a known agonist at the GLP-1 receptor (17), induced GLP-1 like effects, whereas exendin-9-39 amide, an antagonist with a small intrinsic activity in long-term experiments (17), blocked the GLP-1 effect by $\sim 75\%$. We therefore assessed which pathways may be involved in mediating the stimulatory effects of GLP-1 on insulin receptor binding. On pancreatic $\beta$-cells, GLP-1 interacts with specific G protein-coupled receptors, thereby facilitating insulin exocytosis by raising intracellular levels of cAMP and $Ca^{2+}$ (11, 30–32). Our data in RINm5F cells revealed that forskolin and eBIMPS imitated the GLP-1 effect, whereas chelation of intracellular $Ca^{2+}$ by BAPTA-AM completely antagonized the GLP-1 effect. The results indicate that the effect of GLP-1 on insulin binding is mediated by cAMP and $Ca^{2+}$ as second messengers. It should be noted that GLP-1, GIP, and glucagon activate the same pathway. In our experiments, we did not determine the abundance of receptors for glucagon, GIP, or GLP-1 to rule out the possibility that differences in receptor expression may account for the GLP-1-specific effect. There are alternative explanations for our observation that GLP-1 but neither GIP nor glucagon modulated insulin receptor binding in insulinoma cells and monocytes. First, GIP and glucagon receptors may be expressed at a lower level than GLP-1 receptors; second, within the $G_{s}$-cAMP-protein kinase A pathway, $Ca^{2+}$ influx, $Ca^{2+}$ mobilization, and phosphorylation of downstream signaling proteins could show different kinetics when induced by GLP-1, GIP, and glucagon; third, the cross talk between G protein-coupled pathways and tyrosine kinases (e.g., insulin receptor) may be different for GLP-1, GIP, or glucagon (15, 46).

Table 2. Effects of GLP-1 on binding of insulin, proinsulin, or IGF-I on monocytes isolated from healthy subjects, type 1 diabetics, and type 2 diabetics

<table>
<thead>
<tr>
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<th>Specific binding, %/10⁶ mononuclear cells</th>
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<tr>
<td></td>
<td>−GLP-1</td>
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<tr>
<td>Insulin binding</td>
<td></td>
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<tr>
<td>Control</td>
<td>0.83 ± 0.15</td>
</tr>
<tr>
<td>Type 1 diabetics</td>
<td>0.75 ± 0.17</td>
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<tr>
<td>Type 2 diabetics</td>
<td>0.57 ± 0.1*</td>
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<tr>
<td>Proinsulin binding</td>
<td></td>
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<tr>
<td>Control</td>
<td>0.04 ± 0.02</td>
</tr>
<tr>
<td>Type 1 diabetics</td>
<td>0.21 ± 0.1*</td>
</tr>
<tr>
<td>Type 2 diabetics</td>
<td>0.06 ± 0.04</td>
</tr>
<tr>
<td>IGF-I binding</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0.35 ± 0.08</td>
</tr>
<tr>
<td>Type 1 diabetics</td>
<td>0.25 ± 0.06</td>
</tr>
<tr>
<td>Type 2 diabetics</td>
<td>0.31 ± 0.04</td>
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Data are means ± SE; $n = 4$ subjects in each group. IGF-I, insulin-like growth factor I. Cells were incubated for 2 h at 15°C with 10 pM of $^{125}$I-labeled insulin, proinsulin, or IGF-I and with and without 1 µM of unlabeled homologues peptides. Specific $^{125}$I-peptide binding (%) was determined by subtracting the amount of radioactivity bound nonspecifically in the presence of 1 µM unlabeled homologous peptide. $^P < 0.05$, diabetes vs. control. $^P < 0.05$, −GLP-1 vs. +GLP-1 diabetes.
Our observation that GLP-1 but not GIP increases insulin binding may be of clinical relevance and may explain why GLP-1 preserved its activity as an incretin hormone in patients with type 2 diabetes mellitus, whereas GIP did not (33). GLP-1 not only acts as an incretin hormone stimulating postprandial insulin secretion but also enhances peripheral glucose metabolism. The mechanisms underlying the latter effect of GLP-1 remain unclear. It has been suggested that GLP-1 may improve insulin sensitivity in healthy subjects and in diabetic patients (4, 18). Hyperinsulinemic, euglycemic clamp studies in healthy humans showed that GLP-1-(7–36) amide administered for 3 h, leading to circulating levels within the physiological range, does not affect insulin sensitivity (39). It is possible that the conventional techniques for assessing insulin sensitivity in vivo are not sensitive to detect the effect of GLP-1 on insulin binding. Although GLP-1 receptors are reported in a wide variety of tissues (6, 11), it could be possible that the effect of GLP-1 is limited to pancreatic β-cells and not to tissues that comprise the bulk of measured whole body insulin sensitivity. As recently discussed, some controversy remains with regard to the expression of GLP-1 receptors in peripheral tissues (6). Structural variants of the GLP-1 receptor or a second closely related receptor may be expressed in different tissues. Our binding data in monocytes do not completely exclude the existence of GLP-1 receptors. It should be noted that peptide degradation was underestimated by the TCA method, which is suitable to demonstrate gross degradation of peptides but will not give any indication of degradation limited to only a few amino acids. Fragmented GLP-1 may have disturbed the ability of unlabeled GLP-1 to displace the radiolabeled GLP-1 is especially susceptible to degradation by dipeptidyl peptidase IV (present on monocytes), which removes a dipeptide from the NH₂-terminus of the molecule. The resultant metabolite can still bind to the GLP-1 receptor but is unable to transduce a signal because of the loss of the NH₂-terminal dipeptide. This may explain why in monocytes higher concentrations of GLP-1 were needed than in RINm5F cells to modulate insulin and proinsulin binding.

The binding studies in isolated monocytes, a model for the human insulin receptor on peripheral tissues (1, 21, 22), are consistent with the hypothesis that GLP-1 modulates insulin receptor binding. We demonstrated that incubation of isolated monocytes with GLP-1 differentially affected the two types of insulin binding sites. According to our previous findings (21, 22), the low-affinity/high-capacity binding sites were diminished in type 1 and type 2 diabetics but were significantly increased after incubation with GLP-1. It has been elucidated that this binding type is mainly involved in signaling the metabolic activity of insulin (5). The type 2 diabetics were poorly matched in terms of age and body mass index. However, when we investigated insulin binding in a larger cohort of subjects (unpublished observations), we found no significant influence of age, whereas a high body mass index was associated with lower insulin binding. Our data further demonstrate that, in monocytes of control subjects and diabetics, GLP-1 significantly increases proinsulin binding but not IGF-I binding. This underlines the specificity of GLP-1 action and indicates that the high-capacity/low-affinity insulin binding sites are not functional IGF-I receptors.

In summary, our findings in insulinoma cells and in circulating mononuclear cells demonstrate that GLP-1 specifically increases the number of high-capacity/low-affinity insulin binding sites that may be functional proinsulin receptors. Further studies are necessary to elucidate whether the feedback regulation of insulin and proinsulin secretion and the increase of insulin-independent glucose disposal could be attributed to the GLP-1 effect on receptor binding of insulin and proinsulin.

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