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Effects of glucagon-like peptide-I on glucose turnover in rats

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Van Dijk, Gertjan, Stefan Lindskog, Jens J. Holst, Anton B. Steffens, and Bo Ahrén. Effects of glucagon-like peptide-I on glucose turnover in rats. *Am. J. Physiol.* 270 (*Endocrinol. Metab.* 33): E1015–E1021, 1996.—The influences of glucagon-like peptide-I-(7–36) amide (GLP-I; 15 pmol·kg⁻¹·min⁻¹) on glucose turnover were studied in freely moving Wistar rats. In fed rats, GLP-I reduced plasma glucose (from 7.3 ± 0.2 to 5.6 ± 0.3 mmol/l; *P* = 0.017), increased plasma insulin (from 20 ± 3 to 89 ± 11 mU/l; *P* = 0.002), and reduced plasma glucagon (from 44 ± 1 to 35 ± 2 pg/ml; *P* = 0.009) and glucose appearance rate (*R*_a; from 3.9 ± 0.2 to 1.7 ± 0.7 μmol·min⁻¹·100 g⁻¹ after 30 min; *P* = 0.049) without affecting glucose disappearance rate (*R*_d). The glucose clearance rate (MCR) was increased (*P* = 0.048). In 48-h-fasted rats, GLP-I reduced plasma glucose (from 5.0 ± 0.2 to 4.4 ± 0.3 mmol/l; *P* = 0.035) and increased plasma insulin (from 4 ± 1 to 25 ± 10 mU/l; *P* = 0.042) and plasma glucagon (from 43 ± 3 to 61 ± 7 pg/ml; *P* = 0.046). *R*_a and *R*_d were not significantly affected, although *R*_a was lower than *R*_d after 15–30 min (*P* = 0.005) and MCR was increased (*P* = 0.049). Thus GLP-I reduces *R*_a in fed rats and increases MCR in fed and fasted rats. The reduced *R*_a seems mediated by an increased insulin-to-glucagon ratio; the increased glucose clearance seems dependent on insulin and a peripheral effect of GLP-I.

insulin secretion; glucagon secretion; tritiated glucose; fasting

the peptide increased glucose utilization during a hyperglycemic hyperinsulinemic clamp in type 1 diabetic patients (12). Furthermore, GLP-I might also reduce the glucose levels by potentiating the insulin-independent glucose disposal, as has been shown in fasted healthy human subjects (5). This is in agreement with our previous observation that the peptide reduced circulating glucose levels in mice which had been given 2,5-anhydro-D-mannitol, a compound known to inhibit glycogenolysis, gluconeogenesis, and insulin secretion (4). Alternatively, the effects described above might be explained by an inhibitory action of GLP-I on hepatic glucose delivery through a potentiation of the previously described glucose-dependent inhibition of hepatic glucose delivery (19). The differing results indicate that the relative contribution to the glucose-lowering effect of GLP-I by reduction of hepatic glucose delivery vs. stimulation of peripheral glucose disposal is still not established. Neither is it known whether the mechanism of the glucose-lowering effect of GLP-I is different under fasting and fed conditions.

To study further the mechanism of the glucose-lowering effect of GLP-I, we examined the influence of the peptide on hepatic glucose delivery and peripheral glucose disposal by use of the glucose tracer technique in rats under both fed and fasting (48 h) conditions.

MATERIALS AND METHODS

Animals. Male Wistar rats, weighing 290–320 g at the beginning of the present experiment, were used. The animals were individually housed in Plexiglas cages (25 × 25 × 30 cm) at room temperature (20 ± 2°C) and had continuous access to food (Hope farm chow) and water unless otherwise stated. The rats were maintained on a 12:12-h light-dark cycle (0700–1900 light), and they were handled and weighed every day. Under halothane anesthesia and 3 wk before the experiments, all rats were provided with a nonocclusive catheter in the abdominal artery according to techniques described elsewhere (29). This catheter allows frequent arterial blood sampling in freely moving undisturbed rats. For venous infusion of tritiated glucose and/or GLP-I solutions, rats were also provided with a silicon catheter that was inserted in the heart via the right jugular vein (28). Before experiments, catheters were filled with polyvinylpyrrolidone (mol wt 2,500). Patency of the aortic and venous catheters was checked every 3 and 7 days, respectively.

Experimental procedures. All experiments were performed in the light period between 1100 and 1400 in the home cage of the animals. Food was removed from the cage 2 or 48 h before the start of the experiment. One hour before blood sampling, venous and arterial catheters were connected to polyethylene tubes (length 0.4 m, OD 1.25 mm, ID 0.75 mm) filled with citrated saline. Forty-five minutes before the first blood

THE TRUNCATED AMIDATED FORM of glucagon-like peptide-I (GLP-I) is processed from proglucagon in L cells in the distal portion of the gut and is released into the bloodstream during and after food intake (3, 6, 10, 22). GLP-I has been shown to stimulate insulin secretion in both humans and experimental animals (1, 5, 8, 9, 11, 12, 15, 17, 18, 20, 26) and is considered an important incretin factor (3, 6, 10, 22). The peptide also inhibits glucagon secretion (9, 12, 23) and reduces plasma glucose levels (4, 21). Because of this unique pattern of effects, the peptide has attracted great interest as a potential treatment modality in type 2 diabetes (12, 20).

The mechanism underlying the reduced circulating glucose levels by GLP-I has not been established. In overnight-fasted human subjects, infusion of GLP-I reduces hepatic glucose delivery, which most likely is a consequence of increased insulin and decreased glucagon secretion (16). In addition, GLP-I increases the metabolic clearance of glucose, presumably because of increased insulin levels (16). There is also evidence, however, that GLP-I reduces circulating glucose levels by a peripheral insulin-independent action, because

sample, a priming dose of 2.1 μCi D-[3- ^3H]glucose (NET 331, New England Nuclear, Boston, MA), followed by a constant-rate infusion of 93 nCi/min, was delivered intravenously. After withdrawal of each blood sample, an equal amount of citrated blood (10%) was given to avoid diminution of the blood volume. Donor blood was obtained from undisturbed donor rats with permanent heart catheters. In the intervals between withdrawal of each blood sample, the tip of the aortic catheter was filled with 6% citrated saline solution as an anticoagulant. Arterial blood samples of 0.6 ml were taken for determination of plasma concentrations of glucose, insulin, glucagon, and GLP-I and to determine the rate of appearance (R_a) and disappearance (R_d) of glucose. Before the start of intravenous infusion of synthetic GLP-I [proglucagon-(78–107) amide; Peninsula Europe, Merseyside, UK] or vehicle (1% human albumin in serum) at designated time (t) 0, three baseline blood samples were taken at $t = -30$ min, -15 min, and -30 s. The dosage of GLP-I was chosen to deliver $15 \text{ pmol} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$. This dose was selected on the basis of a previous study in rats in which a dose of $\sim 125 \text{ pmol/kg}$ of the similar peptide GLP-I-(7–37) was administered as an intravenous bolus injection in rats and found to augment glucose-stimulated insulin secretion and at the same time be metabolized within 8 min (14). During infusion of GLP-I or vehicle, blood samples were taken at $t = 15, 30, 45, 60,$ and 75 min.

Chemical determinations. Blood samples were immediately transferred to chilled (0°C) centrifuge tubes containing EDTA (0.01%), heparin (500 IU/ml), and aprotinin (trypsin inhibitor, 500 kallikrein inhibitor units/ml) and were centrifuged for 15 min at 5,000 rpm at 4°C . The supernatant was stored at -70°C until analyzed. Determination of plasma glucose concentrations was enzymatically performed in triple 10- μl samples. Rat-specific plasma immunoreactive insulin and glucagon were determined by means of radioimmunoassay kits. Guinea pig serum (for insulin M8309 and for glucagon K5563, both from Novo Nordisk, Bagsvaerd, Denmark) served as antisera. A second antibody binding to donkey anti-rabbit antibody-coated cellulose particles (SAC-CEL ASAC 1; Immuno Diagnostics, UK) was performed for glucagon analysis. Plasma concentrations of GLP-I were measured with a radioimmunoassay after extraction with ethanol, as previously described (24). The antiserum used (code no. 89390) is highly specific for GLP-I of intestinal origin. Analytic procedures for [^3H]glucose were performed as previously described (30).

Calculations and statistics. Glucose R_a and R_d were calculated using Steele's equations (27), which allow determinations in steady-state as well as non-steady-state conditions. The volume of distribution in which rapid changes in glucose concentration and specific activity of [^3H]glucose take place was set to 188 ml/kg (25). R_a and R_d values in Figs. 2, 4, and 5 are demonstrated between the time points for the samples used for their calculations. For example, when samples taken at $t = 15$ and $t = 30$ min were used for the calculation, the R_a and R_d are shown at $t = 22.5$ min. The clearance of glucose was calculated by glucose R_d divided by plasma glucose concentrations. All results are presented as means \pm SE. For statistical evaluation of the data, Student's paired and unpaired t -tests were used.

RESULTS

Fed rats. On the experimental day, the ad libitum-fed rats receiving the GLP-I solution ($n = 5$) and vehicle ($n = 6$) weighed 357 ± 8 and 353 ± 5 g, respectively. Table 1 shows the baseline plasma glucose, insulin, and

Table 1. Baseline levels of plasma insulin, glucagon, glucose, and GLP-I, the glucose R_a and R_d , and the MCR in freely fed and 48-h-fasted rats

	Fed Rats ($n = 11$)	Fasted Rats ($n = 10$)	P
Insulin, mU/l	23.0 ± 1.6	3.9 ± 1.1	<0.001
Glucagon, pg/ml	46 ± 1	44 ± 2	0.96 (NS)
Glucose, mmol/l	7.2 ± 0.1	5.1 ± 0.1	<0.001
GLP-I, pmol/l	18.5 ± 1.7	12.6 ± 1.3	0.013
Glucose R_a , $\mu\text{mol} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$	3.8 ± 0.2	1.5 ± 0.1	<0.001
Glucose R_d , $\mu\text{mol} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$	3.7 ± 0.1	1.4 ± 0.1	<0.001
MCR, $\text{ml} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$	0.51 ± 0.01	0.27 ± 0.02	<0.001

Values are means \pm SE. GLP-I, glucagon-like peptide-I. Glucose rates of appearance (R_a) and disappearance (R_d) and the glucose clearance rate (MCR) were calculated after 30–45 min of infusion of D-[3- ^3H]glucose. P indicates the probability level of random difference between the 2 groups; NS indicates no significant difference ($P > 0.050$).

glucagon levels as well as the R_a , the R_d , and the clearance rate of glucose. Fig. 1 shows the plasma levels of glucose, insulin, and glucagon before and during infusion of GLP-I ($n = 5$) or vehicle ($n = 6$) in the fed rats. Intravenous infusion of GLP-I reduced the plasma glucose levels from 7.3 ± 0.2 to 5.6 ± 0.3 mmol/l at 30 min, i.e., by 1.7 ± 0.5 mmol/l ($P = 0.017$). Thereafter the glucose levels gradually returned toward the preinfusion levels. Furthermore, GLP-I markedly, although transiently, increased plasma insulin levels from 20 ± 3 to 89 ± 11 mU/l after 15 min of infusion, i.e., by 69 ± 10 mU/l ($P = 0.002$). After 15 min of infusion, the plasma insulin levels returned to baseline despite the ongoing GLP-I infusion. The plasma insulin levels did not drop below those in the controls, even though the plasma glucose levels were lower. Plasma glucagon levels were constantly reduced during the GLP-I infusion, being 44 ± 1 pg/ml before GLP-I infusion and 35 ± 2 pg/ml after 45 min of peptide infusion ($P = 0.009$). After 15 min of GLP-I infusion, the plasma insulin-to-plasma glucagon ratio was 2.5 ± 0.4 $\mu\text{U/pg}$, whereas the corresponding ratio in saline-infused controls was 0.39 ± 0.03 $\mu\text{U/pg}$ ($P = 0.009$). In the vehicle-infused control rats, no significant changes were observed in plasma glucose, insulin, or glucagon levels.

Figure 2 shows the R_a and R_d of glucose during the infusion of GLP-I and vehicle in fed rats. R_a was significantly reduced during the first 30 min of GLP-I infusion, because it fell from 3.9 ± 0.2 $\mu\text{mol} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$ before the start of GLP-I infusion to 1.7 ± 0.7 $\mu\text{mol} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$ during 30 min of infusion ($P = 0.049$). After 30 min, R_a returned to control levels despite the ongoing infusion of GLP-I and the constantly reduced plasma glucagon levels. In contrast, R_d was not significantly affected by GLP-I. It was 3.6 ± 0.2 $\mu\text{mol} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$ before and 3.1 ± 0.2 $\mu\text{mol} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$ after 30 min of infusion [not significant (NS)]. At the same time, however, plasma glucose values were lowered by GLP-I (see Fig. 1). Hence the glucose clearance rate, i.e., glucose R_d -to-plasma glucose ratio,

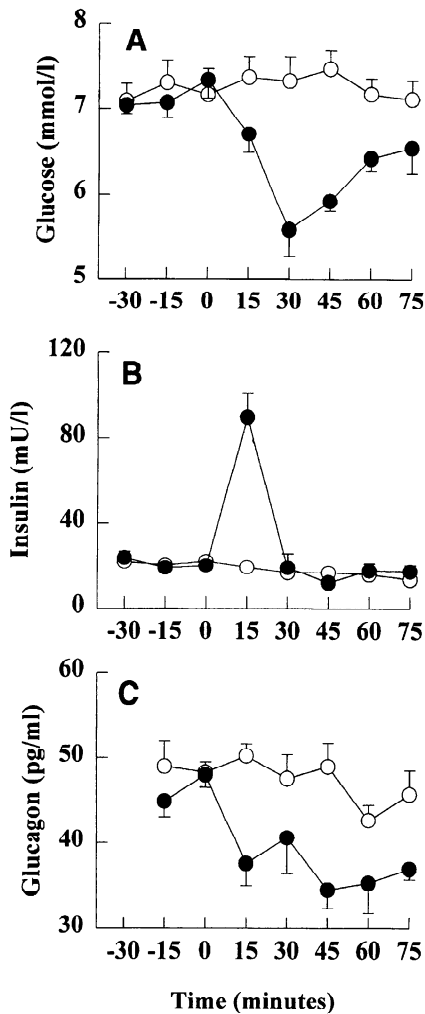


Fig. 1. Plasma glucose (A), insulin (B), and glucagon concentrations (C) in freely fed rats intravenously infused with glucagon-like peptide-I (GLP-I; $n = 5$; $15 \text{ pmol} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$; ●) or vehicle ($n = 6$; ○). During experiments, all rats were infused with D-[3- ^3H]glucose from $t = -75 \text{ min}$, i.e., 45 min before the first blood sample. The infusion of GLP-I or vehicle started at *time 0*. Values are means \pm SE.

was significantly increased by GLP-I, because it was $0.56 \pm 0.04 \text{ ml} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$ after 30 min of peptide infusion compared with $0.43 \pm 0.04 \text{ ml} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$ after infusion of vehicle ($P = 0.048$). Infusion of the vehicle did not significantly alter R_a , R_d , or the clearance rate of glucose.

Fasted rats. On the experimental day, the 48-h-fasted rats receiving the GLP-I solution ($n = 5$) and vehicle ($n = 5$) weighed 320 ± 7 and $320 \pm 4 \text{ g}$, respectively. During the fasting period, rats lost on average $49 \pm 2 \text{ g}$ of body weight. Table 1 shows the baseline plasma glucose, insulin, and glucagon levels as well as the R_a , the R_d , and the clearance rate of glucose in the 48-h-fasted rats. Figure 3 shows the plasma glucose, insulin, and glucagon levels in the 48-h-fasted rats infused with GLP-I ($n = 5$) or vehicle ($n = 5$). As in the fed rats, the intravenous infusion of GLP-I reduced the plasma glucose levels also in the fasted rats, from $5.0 \pm 0.2 \text{ mmol/l}$ before the infusion to $4.4 \pm 0.3 \text{ mmol/l}$ after 30 min of infusion, i.e., by $0.6 \pm 0.2 \text{ mmol/l}$ ($P = 0.035$).

Thereafter, plasma glucose levels gradually returned to baseline values. Similarly to the fed rats, GLP-I induced a transient increase in plasma insulin levels in the fasted rats, from 4 ± 1 to $25 \pm 10 \text{ mU/l}$ after 15 min of infusion, i.e., by $21 \pm 8 \text{ mU/l}$ ($P = 0.042$). Thereafter, the insulin values returned to the low baseline levels despite the ongoing GLP-I infusion. As in the fed rats, plasma insulin levels never dropped below control values, yet plasma glucose levels were lower in GLP-I than in vehicle-infused rats. In contrast to what was observed in the fed rats, plasma glucagon levels transiently increased during the GLP-I infusion in the 48-h-fasted rats, from 43 ± 3 to $61 \pm 7 \text{ pg/ml}$, i.e., by $18 \pm 6 \text{ pg/ml}$ after 30 min of infusion ($P = 0.046$). The peak glucagon values coincided with the nadir glucose value; thereafter glucagon levels returned to preinfusion values. After 15 min of GLP-I infusion, the plasma insulin-to-plasma glucagon ratio was $0.49 \pm 0.18 \text{ } \mu\text{U/pg}$, whereas the corresponding ratio in vehicle-infused controls was $0.06 \pm 0.02 \text{ } \mu\text{U/pg}$ ($P = 0.041$). However, after 30 min of infusion, the plasma insulin-to-plasma glucagon ratio had returned to $0.11 \pm 0.04 \text{ } \mu\text{U/pg}$ in the GLP-I-infused animals vs. $0.06 \pm 0.02 \text{ } \mu\text{U/pg}$ in the controls (NS). In the vehicle-infused control rats, no significant changes were observed in plasma glucose, insulin, or glucagon levels.

Figure 4 shows the glucose R_a and R_d during infusion of GLP-I and vehicle in the 48-h-fasted rats. Neither the glucose R_a nor the glucose R_d was significantly affected by GLP-I. R_a was significantly lower than R_d at the interval of 15–30 min after start of GLP-I infusion (0.83 ± 0.15 vs. $1.63 \pm 0.15 \text{ } \mu\text{mol} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$; $P =$

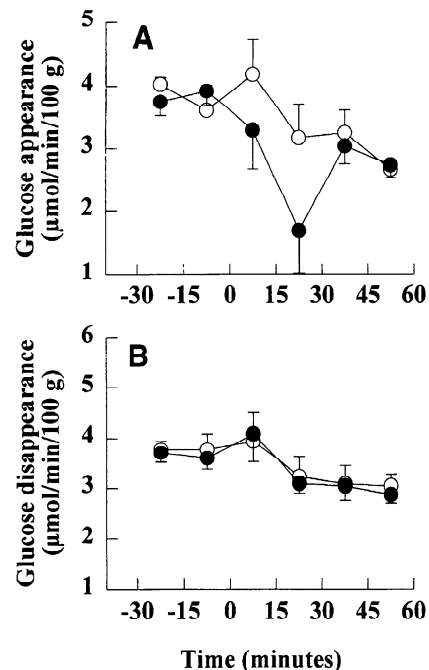


Fig. 2. Glucose rates of appearance (A) and disappearance (B) in freely fed rats intravenously infused with GLP-I ($n = 5$; $15 \text{ pmol} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$; ●) or vehicle ($n = 5$; ○). Infusions are as described in Fig. 1. Values (means \pm SE) are calculated from changes between 2 time points and are reported here between those 2 time points.

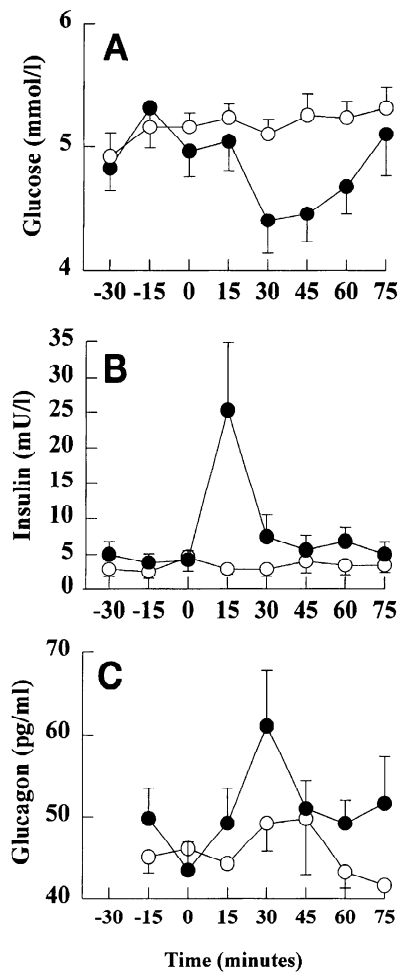


Fig. 3. Plasma glucose (A), insulin (B), and glucagon concentrations (C) in rats fasted for 48 h and infused intravenously with GLP-I ($n = 5$; $15 \text{ pmol} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$; ●) or vehicle ($n = 5$; ○). Infusions are as described in Fig. 1. Values are means \pm SE.

0.005; Fig. 5), which was at the time point when plasma glucose values were lowered by GLP-I (see Fig. 3). The glucose clearance rate, i.e., glucose R_d -to-plasma glucose ratio, was significantly higher after 30 min of infusion with GLP-I, $0.38 \pm 0.04 \text{ ml} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$, than during infusion of vehicle, $0.26 \pm 0.03 \text{ ml} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$ ($P = 0.049$). Vehicle infusion did not significantly alter glucose R_a , glucose R_d , or the clearance of glucose in the fasted rats.

Plasma GLP-I levels. Table 1 and Fig. 6 show plasma GLP-I levels before and during infusion of GLP-I and vehicle in freely fed and 48-h-fasted rats. The baseline plasma GLP-I levels were significantly higher in fed rats ($18.5 \pm 1.7 \text{ pmol/l}$) than in 48-h-fasted rats ($12.6 \pm 1.3 \text{ pmol/l}$; $P = 0.013$). The plasma GLP-I levels in fed and fasted rats during GLP-I infusions were not significantly different.

DISCUSSION

In the present study, we found that GLP-I transiently reduces the R_a of glucose by 31% in freely fed rats, without affecting the R_d of glucose. This resulted in a transient reduction of plasma glucose levels by 1.7 mmol/l (Fig. 1). The clearance rate of glucose, i.e., the

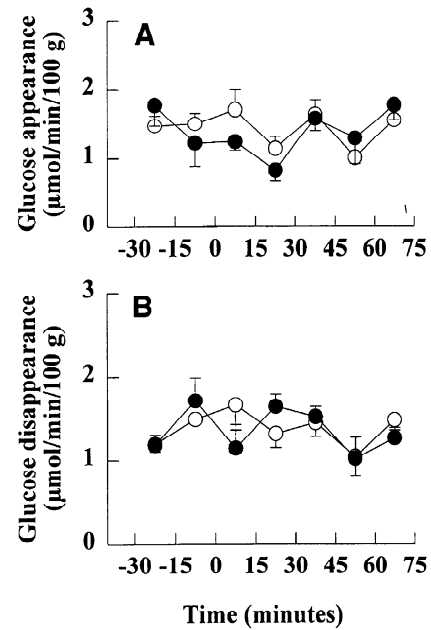


Fig. 4. Glucose rates of appearance (A) and disappearance (B) in rats fasted for 48 h and infused intravenously with GLP-I ($n = 5$; $15 \text{ pmol} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$; ●) or vehicle ($n = 5$; ○). Infusions are as described in Fig. 1. Values (means \pm SE) are calculated from changes between 2 time points and are reported here between those 2 time points.

rate by which each circulating millimole of glucose is cleared, was increased during GLP-I infusion, because glucose R_d remained unaffected whereas plasma glucose levels decreased. Furthermore, the study demonstrates that the peptide increases plasma insulin and reduces plasma glucagon in fed rats. We interpret these findings to indicate that GLP-I in fed rats markedly increases the insulin-to-glucagon ratio, which reduces hepatic glucose output. The insulinotropic action of GLP-I vanished after 30 min, and, as a result, the low glucose R_a increased again toward control values. Thus, despite levels of plasma glucagon constantly remaining low, GLP-I only transiently influenced glucose R_a . At the same time, GLP-I increases the efficacy of peripheral glucose uptake, which might be an effect mediated by insulin or directly stimulated by GLP-I.

Our results confirm the previously reported study in overnight-fasted humans, in which GLP-I reduced the

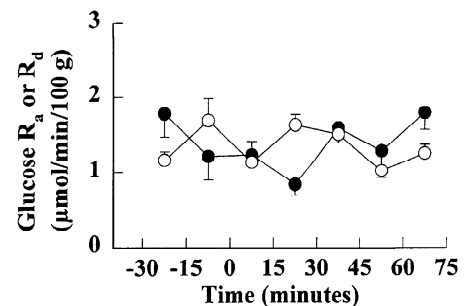


Fig. 5. Glucose rates of appearance (glucose R_a ; ●) and disappearance (glucose R_d ; ○) before and during intravenous infusion of GLP-I ($15 \text{ pmol} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) in 48-h-fasted rats. Values (means \pm SE) are calculated from changes between 2 time points and are reported here between those 2 time points. R_a and R_d were significantly different at $t = 22.5 \text{ min}$ ($P = 0.005$).

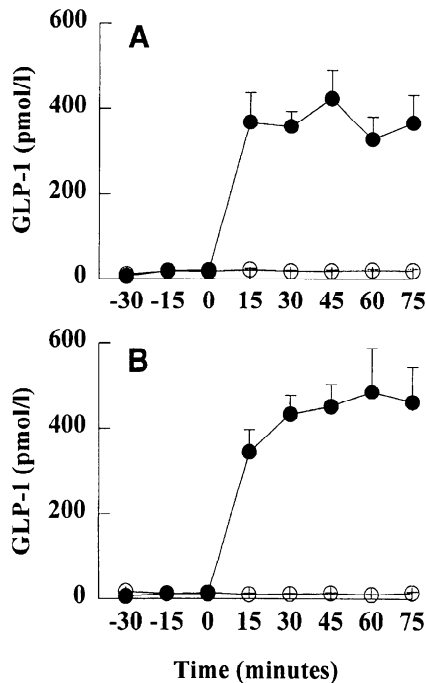


Fig. 6. Plasma GLP-I concentrations before and during intravenous infusion of GLP-I ($15 \text{ pmol} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$; ●) or vehicle (○) in freely fed rats (A) and in rats fasted for 48 h (B). Infusions started at time 0. Values are means \pm SE for 5–6 rats in each group.

R_a and lowered circulating glucose without affecting the R_d (16). Our result, that GLP-I increased the glucose clearance, also confirms the studies by Gutniak et al. (12), showing that GLP-I increases insulin sensitivity during a hyperglycemic clamp in type 1 diabetics, and by D'Alessio et al. (5), showing that GLP-I potentiates insulin-independent glucose disposal. Finally, the results corroborate our recent studies in mice, demonstrating that GLP-I lowers plasma glucose both in insulin-deficient alloxan-diabetic mice (2) and after inhibition of liver gluconeogenesis, liver glycogenolysis, and insulin secretion from B cells by 2,5-anhydro-D-mannitol in normal mice (4). Therefore, we conclude that GLP-I reduces glucose levels by a hepatic, but possibly also by a peripheral effect, the hepatic effect being the result of an increased insulin-to-glucagon ratio.

In the present study, infusion of GLP-I led to increased plasma insulin levels and reduced plasma glucose levels in both the fed and the fasted state. In the fasted rats, no significant differences were observed in absolute values of R_a or R_d during the intravenous infusion with GLP-I. However, at 15–30 min after start of the infusion, R_d was significantly higher than R_a , which would suggest a change in the R_a - R_d balance, indicative of a stimulated clearance of glucose. The main mechanism underlying the glucose-reducing effect of GLP-I under fasting conditions is therefore probably a stimulated clearance of glucose. The fact that glucose R_a was not altered during GLP-I infusion in fasted rats is probably due to the fact that the increase in the ratio of plasma insulin to plasma glucagon was low in these rats. During GLP-I infusion

in fasted rats, plasma glucagon levels were not reduced. This was not expected, because GLP-I has previously been shown to inhibit glucagon secretion in humans (12) as well as in experimental animals, including rodents (9, 23). It is likely that the hypoglycemic action of GLP-I under the 48-h-fasting condition led to an increased activation of the sympathoadrenal system (13), which may have counteracted the direct inhibitory action of GLP-I on glucagon secretion. Taken together, the results of the present study indicate that the glucose-lowering effect of GLP-I in fasted rats is mediated by stimulated glucose clearance rate and that the reduced R_a , which is seen only under fed conditions, is not directly mediated by GLP-I. Rather, the reduced R_a seems to be mediated by the increased insulin-to-glucagon ratio in plasma, which was markedly increased by GLP-I under fed conditions but only mildly increased during fasting conditions. It cannot be excluded, however, that GLP-I in addition to its effects via pancreatic hormone secretion also directly reduces R_a and that this effect was simply counteracted by the rising plasma glucagon levels due to hypoglycemia under fasting conditions. Therefore more direct studies of the effects on GLP-I on liver cell glucose metabolism are required.

Insulin secretion was clearly and markedly stimulated by GLP-I, although this effect was more pronounced under fed than under fasted conditions. This could not be attributed to differences in concentrations of GLP-I in the circulation, because the infusion of GLP-I led to similar levels of plasma GLP-I in fed and fasted rats. Thus this observation may reinforce the idea that the insulinotropic action of GLP-I is glucose dependent (3, 6, 10, 21). In particular, a recent study in the mouse showed a more marked insulinotropic action of GLP-I under fed conditions than during fasting (1). The finding in the present study, that the increased plasma insulin levels returned to preinfusion values already during the ongoing infusion of the peptide, has previously been demonstrated in humans as well (21). This phenomenon might be explained by the gradual lowering of plasma glucose levels, which weakens the insulin secretory action of the peptide. However, because the plasma glucose levels, at least under fed conditions, were still above levels required for the insulinotropic action of GLP-I, other explanations are also possible. For example, it may be speculated that GLP-I has induced a desensitization on the B cells during its infusion, as has been suggested from studies on the effect of GLP-I on adenosine 3',5'-cyclic monophosphate production in cultured cell lines transfected to express the GLP-I receptor (31). Whether desensitization occurs of GLP-I receptors located on B cells in vivo remains to be studied.

A question that still remains to be solved is whether the effects on glucose turnover observed during GLP-I infusion, i.e., reduced R_a in fed rats and increased glucose clearance rate in both fed and fasted animals, are solely mediated by the increased insulin-to-glucagon ratio or whether a direct action of GLP-I contributes to these phenomena. The increased glucose clear-

ance induced by GLP-I could be at least partially mediated by a direct action of the peptide, because it was of the same magnitude in fed and fasted conditions, yet the insulinotropic action of the peptide was weaker under fasted conditions. Furthermore, because glucose R_d was unaffected during GLP-I infusion, an insulin-independent action seems to contribute to the increased glucose clearance. However, the exact mechanism underlying the increased glucose clearance during GLP-I infusion remains to be established.

In conclusion, we have demonstrated that the mechanism of the plasma glucose-reducing effect of GLP-I in the rat is dependent on the nutritional status. Thus, in the freely fed state, the peptide reduces plasma glucose by reducing hepatic glucose delivery and increasing the clearance rate of glucose, whereas, under fasting conditions, the glucose-lowering effect of GLP-I is mediated mainly by increasing the glucose clearance rate. Furthermore, our study presents evidence that the reduced glucose R_a induced by GLP-I is secondary to increased insulin and reduced glucagon secretion, whereas the stimulation of the increased clearance rate of glucose seems to be at least partially secondary to a direct peripheral effect of GLP-I. Because diabetes is accompanied by inappropriately elevated hepatic glucose production and reduced glucose clearance (7), the inhibition of hepatic glucose output and the stimulation of the peripheral glucose uptake by GLP-I, together with its effects to stimulate insulin secretion and inhibit glucagon secretion, reinforce the need for further studies to explore the use of this substance or its analogues in the treatment of diabetes.

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