Glucose Competence of the Hepatoportal Vein Sensor Requires the Presence of an Activated Glucagon-Like Peptide-1 Receptor

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Activation of the hepatoportal glucose sensors by portal glucose infusion leads to increased glucose clearance and induction of hypoglycemia. Here, we investigated whether glucagon-like peptide-1 (GLP-1) could modulate the activity of these sensors. Mice were therefore infused with saline (S-mice) or glucose (P-mice) through the portal vein at a rate of 25 mg/kg·min. In P-mice, glucose clearance increased to 67.5 ± 3.7 mg/kg·min as compared with 24.1 ± 1.5 mg/kg·min in S-mice, and glycemia decreased from 5.0 ± 0.1 to 3.3 ± 0.1 mmol/l at the end of the 3-h infusion period. Co-infusion of GLP-1 with glucose into the portal vein at a rate of 5 pmol/kg·min (P–GLP-1 mice) did not increase the glucose clearance rate (57.4 ± 5.0 ml/kg·min) and hypoglycemia (3.8 ± 0.1 mmol/l) observed in P-mice. In contrast, co-infusion of glucose and the GLP-1 receptor antagonist exendin-(9-39) into the portal vein at a rate of 25 mg/kg·min as compared with 0.5 pmol/kg·min (P–Ex mice) reduced glucose clearance to 36.1 ± 2.6 ml/kg·min and transiently increased glycemia to 9.2 ± 0.3 mmol/l at 60 min of infusion before it returned to the fasting level (5.6 ± 0.3 mmol/l) at 3 h. When glucose and exendin-(9-39) were infused through the portal and femoral veins, respectively, glucose clearance increased to 70.0 ± 4.6 ml/kg·min and glycemia decreased to 3.1 ± 0.1 mmol/l, indicating that exendin-(9-39) has an effect only when infused into the portal vein. Finally, portal vein infusion of glucose in GLP-1 receptor−/− mice failed to increase the glucose clearance rate (26.7 ± 2.9 ml/kg·min). Glycemia increased to 8.5 ± 0.5 mmol/l at 60 min and remained elevated until the end of the glucose infusion (8.2 ± 0.4 mmol/l). Together, our data show that the GLP-1 receptor is part of the hepatoportal glucose sensor and that basal fasting levels of GLP-1 sufficiently activate the receptor to confer maximum glucose competence to the sensor. These data demonstrate an important extrapancreatic effect of GLP-1 in the control of glucose homeostasis. Diabetes 50:1720–1728, 2001

After a meal, glucose is absorbed by the intestine and collected into the hepatoportal vein. A positive glucose concentration gradient between the hepatoportal vein and arterial blood is thus established. Glucose-sensitive units present in the hepatoportal vein detect this gradient (1–3) and send a signal through the hepatic branch of the vagus nerve to target tissues such as the liver (4–8), the hypothalamus (9,10), insulin-secreting β-cells (11), the brain stem (12), and the adrenal glands (13,14). The specific cellular functions that are activated then participate in the adaptation of the body to the new metabolic situation. We previously described that one of the consequences of activating the hepatoportal glucose sensor was an increase in blood glucose clearance and utilization in a subset of tissues, mostly heart, soleus, and brown adipose tissue (15). We also showed that activation of this sensor was inhibited by somatostatin and that it required the presence of the glucose transporter GLUT2 (16).

The best-described glucose sensing system is the insulin-secreting pancreatic β-cells (17). In these cells, glucose induces insulin secretion by a mechanism that depends on glucose metabolism. This secretory activity can be strongly potentiated by hormones such as the glucagon-like peptide-1 (GLP-1). This hormone is secreted postprandially by intestinal L-cells in the portal vein and reaches the pancreatic β-cells, where it binds to a specific plasma membrane G protein–coupled receptor linked to the adenylyl cyclase pathway. The consequent rise in intracellular cAMP content potentiates the glucose signal, leading to insulin secretion (18–20). Based on the β-cell model, we hypothesized that GLP-1 could also modulate the activity of the hepatoportal glucose sensor. This hypothesis was supported by the finding that GLP-1 can control the firing rate of the hepatic branch of the vagus nerve, which is controlled by the hepatoportal glucose sensor (21,22). The active form of GLP-1 is GLP-1(7-37) or GLP-1(7-36)amide; it is also intriguing that the half-life of GLP-1(7-37) and GLP-1(7-36)amide is very short (~0.5 min) because of a rapid proteolytic cleavage of the first two NH₂-terminal amino acids by dipeptidylpep-
capillaries adjacent to GLP-1–secreting L-cells have been shown to produce a high level of this enzyme (23), suggesting an explanation for the very rapid inactivation of this peptide. This observation also suggests that the hepatoportal sensor may be the target exposed to the highest circulating concentration of active GLP-1. Recently, it has been shown that coinfusion of GLP-1 and glucose in the portal vein increases insulin secretion through activation of a neuronal mechanism (24).

Here, we analyze the role of GLP-1 and its receptor in the regulation of the hepatoportal vein glucose sensor. The induction of hypoglycemia and the increase in glucose clearance induced by portal-vein glucose infusion were not modified by coinfusion of GLP-1, although they were suppressed by the GLP-1 receptor agonist exendin-(9-39) (25). Therefore, these data suggest that occupation of the GLP-1 receptor by its ligand is required to maintain the glucose competence of the hepatoportal glucose sensor, thereby identifying a novel extrapancreatic function of GLP-1 in the control of glucose homeostasis.

RESEARCH DESIGN AND METHODS

Surgical procedure for catheter implantation. Under pentobarbital anesthesia (65 mg/kg i.p.), a first catheter was implanted into the hepatoportal vein through the splenic vein of 12- to 16-week-old C57BL6 mice (IFFA-CREDO, L’arbresle, France) as well as GLP-1 receptor knockout mice, as previously described (25). After 4–6 days, allowing for full body-weight recovery, one extremity of a second catheter was implanted into the femoral vein under similar anesthetic conditions. The other extremity of the catheter was tunneled under the skin of the back, exteriorized, and secured in place at the back of the neck. The mice were then allowed to recover from the surgery in individual cages. The GLP-1R−/− mice were of a mixed CD1 and SV129 background and have been extensively characterized (25). Control mice were C57BL6, a strain that behaved in a manner similar to C57BL6xSV129 in our present glucose infusion protocol (15).

Infusion procedures. At 5–7 days after catheter implantations, the mice were fasted for 6 h. A 33% glucose solution was infused for 180 min through either the portal or femoral vein at a rate of 2 μl/min (corresponding to ~35 nmol/kg/min; Table 1) and a constant rate of 3 μmol/l (15). A steady state specific activity was reached after 180 min, as shown in Fig. 1A. In contrast, where glucose was infused at the same rate through the femoral vein (F-mice), a transient hyperglycemia was observed. Infusion of saline through the portal vein did not modify the basal glycemic levels. The AUC relative to the basal glycemic levels indicates a significant decrease in the glycemic profile in P-mice (—138 ± 28 mmol/l·min) and a significant increase in F-mice (324 ± 50 mmol/l·min) compared with S-mice (22 ± 58 mmol/l·min) (Fig. 1A, inset). Blood glucose clearance (Fig. 1B) was strongly increased in P-mice (67.5 ± 3 ml/kg·min) compared with both S- and F-mice (27.1 ± 1.5 ml/kg·min and 30.7 ± 1.7 ml/kg·min, respectively). The difference in glycemic profiles and glucose clearance between P- and F-mice could not be explained by differences in insulin profiles or in insulin AUCs during the course of the experiments, as shown in Fig. 1C. These data indicate that activation of the hepatoportal sensor increased glucose clearance and induced hypoglycemia. They are similar to those previously reported (15).

GLP-1 infusion into the portal vein does not further increase stimulation of the hepatoportal sensor by glucose. To investigate whether GLP-1 could further activate the hepatoportal glucose sensor, we infused the peptide with glucose into the portal vein of control mice (P–GLP-1 mice) at a rate of 5 μmol/kg·min. This increased plasma GLP-1 concentration to 69 ± 14 pmol/l, as assessed at completion of the infusion experiment. In these mice, hypoglycemia reached 3.8 ± 0.1 mmol/l at 180 min of infusion. Coinfusion of GLP-1 in portal saline-infused or in femoral glucose-infused mice led to glycemic profiles and AUCs that were not different from those obtained when GLP-1...
was omitted (Fig. 2A and compare with Fig. 1A). The blood glucose AUCs relative to the basal values are shown in Fig. 2A (inset). Blood glucose clearance was increased to 57.4 ± 5.0 ml/kg·min in P–GLP-1 mice, which is significantly higher than in S–GLP-1 and F–GLP-1 mice (24.9 ± 2.6 and 32.0 ± 1.3 ml/kg·min, respectively) (Fig. 2B) but not different from that of P-mice (67.5 ± 3 ml/kg·min) (Fig. 1B). However, the insulinemic profiles and insulin AUCs were higher when GLP-1 was coinfused into the portal vein as compared with the femoral vein (AUC 3,570 ±
472 vs. 2,352 μU·min/ml, respectively) (Figs. 2C and 1C, insets). When GLP-1 was coinfused with glucose into the portal vein at rates of 0.5 or 50 pmol/kg·min (n = 5, data not shown), the same glycemic profiles and glucose clearance rates were obtained as when the infusion rate was 5 pmol/kg·min. These data indicate that exogenous infusion of GLP-1 in the portal vein did not modify the activity of the hepatoporal glucose sensor, as measured by the induction of hypoglycemia and the increase in glucose clearance, but it increased insulin AUCs.

FIG. 2. No effect of exogenous GLP-1 on activation of the hepatoporal glucose sensor. Glucose was infused at a rate of 25 mg/kg·min and GLP-1 was infused at a rate of 5 pmol/kg·min through the portal (P–GLP-1, △) or the femoral (F–GLP-1, ◇) vein of mice. Data were compared with saline infused mice (S–GLP-1, ○). A: Glycemic pattern of the infused mice (I). The mean AUC of the blood glucose concentration values relative to the fasting values is also shown (II). Each data point is the mean ± SE for n ≥ 6 for each group. B: Blood glucose clearance calculated during the last hour of the infusion. C: Insulinemia during the glucose or saline infusion protocols (I). The mean AUC of the blood glucose concentration values relative to the fasting values is also shown (II). Data are the means ± SE for five to six mice per group. *Statistically different from P–GLP-1 mice; #statistically different from S–GLP-1 mice; P < 0.05.
Portal infusion of exendin-(9-39) prevents activation of the hepatoportal glucose sensor. Because GLP-1 is released by intestinal L-cells directly into the portal vein, we hypothesized that the absence of effect of exogenous GLP-1 on the hepatoportal sensor could be because of an occupancy of the receptor producing a maximal effect on the sensor. Exendin-(9-39), which is an inverse agonist of the GLP-1 receptor (26,27), was therefore coinfused with glucose into the portal vein (P-Ex mice). Confusion of exendin-(9-39) into the portal vein at a rate of 0.05 pmol/kg/min did not consistently inhibit the increased glucose clearance rate (not shown). When this rate of confusion was increased to 0.5 pmol/kg/min, there was a complete suppression of the hypoglycemia-inducing effect, and instead, glycemia rose from 5.7 ± 1 to 9.2 ± 0.3 mmol/l 60 min after the beginning of the infusion and progressively returned to the fasting value of 5.6 ± 0.3 mmol/l at the end of the infusion period (Fig. 3A). The blood glucose AUC of the P-Ex mice was 244 ± 24 mmol/l·min, significantly higher than the corresponding value for P-mice (–138 ± 28 mmol/l·min) (Fig. 3A inset, compare with Fig. 1B inset). When exendin-(9-39) was coinfused with glucose into the portal vein at rates of 5 or 50 pmol/kg/min (n = 8 and 4, respectively, data not shown), the same glycemic profiles and glucose clearance rates were obtained as when the infusion rate was 0.5 pmol/kg·min.

Importantly, however, we found that when glucose was infused into the portal vein and exendin-(9-39) was infused into the femoral vein at the rate of 0.5 pmol/kg·min, increases in glucose clearance and hypoglycemia were still induced. Therefore, this strongly suggests that the primary site of action of exendin is on the hepatoportal sensor itself. Infusion of exendin-(9-39) with saline into the portal vein only minimally affected the glycemic profile, but infusion into the femoral vein with glucose prevented the return of glycemia to the basal value after it had reached a maximal level of 9.4 ± 0.9 mmol/l, 60 min after the beginning of the infusion (Fig. 3A).

The effect of exendin-(9-39) on the hepatoportal sensor was further evidenced when measuring glucose clearance rates and insulin profiles. Glucose clearance was markedly reduced in P-Ex mice (36.1 ± 2.6 ml/kg·min) compared with P- and P-GLP-1 mice (67.5 ± 3 and 57.4 ± 5.0 ml/kg·min, respectively), although it was still significantly higher than when the mice were infused with exendin-(9-39) alone (S-Ex mice, 27.7 ± 2.1 ml/kg·min). Importantly, the glucose clearance of mice receiving exendin-(9-39) through the femoral vein and glucose through the portal vein (P-fEx mice) was still increased to a level similar to that seen in P-mice and P-GLP-1 mice (Fig. 3B, compare with Figs. 1B and 2B). Finally, the insulin profiles of the P-Ex mice and F-Ex mice were similar, as were their insulin AUCs (Fig. 3C).

However, a significant reduction in insulin AUC was obtained in P-fEx mice compared with P-Ex mice, even though glucose clearance values were similar.

Lack of stimulation by glucose of the hepatoportal glucose sensor in GLP-1 receptor−/− mice. To further evaluate the role of GLP-1 and its receptor in the function of the hepatoportal glucose sensor, we performed glucose infusion and metabolic measurements in GLP-1-receptor−/− mice. When glucose was infused into the portal vein of mutant mice (P-GLP-1R−/− mice), the blood glucose concentration increased from 6.0 ± 0.5 to 8.5 ± 0.5 mmol/l 60 min after the beginning of the infusion and remained elevated until the end of the infusion period (Fig. 4A). This profile is similar to that of P-Ex mice, except that in these mice, glycemia progressively returned to basal values (Fig. 3A). The profile of P-GLP-1R−/− was, however, similar to that of mutant mice infused with glucose and exendin-(9-39) through the femoral vein. The blood glucose clearance in P-GLP-1R−/− mice was not increased over the value of the S-GLP-1R−/− mice (26.7 ± 2.0 and 28.7 ± 0.5 ml/kg·min, respectively) and was also similar to that of F-GLP-1R−/− mice (Fig. 4B). Fasting plasma insulin levels were higher in mutant than in control mice. Insulinemic levels were nevertheless still increased by either portal or femoral glucose infusion (Fig. 4C).

DISCUSSION

In the present study, we evaluated the role of GLP-1 and its receptor on the activation of the hepatoportal glucose sensor. We show that portal coinfusion of GLP-1 with glucose did not further activate the hepatoportal sensor. In contrast, coinfusion into the portal vein of the receptor antagonist exendin-(9-39) with glucose strongly inhibited its activation. Finally, studies with GLP-1 receptor–null mice also showed loss of glucose sensor activation. These data demonstrate that the GLP-1 receptor is required for the function of the hepatoportal glucose sensor and that, in the fasted state, it is already sufficiently activated to maintain the glucose competence of the sensor.

We recently reported that stimulation of the hepatoportal glucose sensor by a portal glucose infusion induced hypoglycemia associated with an increase in glucose clearance. This resulted, at least in part, from stimulation of glucose utilization in a subset of tissues including soleus muscle, heart, and brown adipose tissue (15). We further demonstrated that activation of this sensor could be inhibited by somatostatin and that it was dependent on the presence of GLUT2 (16). These data revealed an important function of the hepatoportal sensor in the control of glucose homeostasis, which may be particularly active in the postprandial state, when absorbed nutrients rapidly appear in the portal circulation. These data also suggested a similarity between glucose sensing by this portal sensor and the pancreatic β-cells. To further study this possible similarity, we evaluated whether GLP-1, the most potent insulinotropic hormone known so far, could also participate in the activation of the portal sensor. Our first experiments were therefore aimed at evaluating whether coinfusion of GLP-1 and glucose into the portal vein would further increase the activation of the portal sensor by glucose. If this were the case, hypoglycemia and the glucose clearance rate would be increased. In contrast to these expected results, portal coinfusion of GLP-1 with glucose did not change any of these parameters. This was observed with a GLP-1 infusion rate of 5 pmol/kg·min (which increases plasma GLP-1 levels to threefold the fasting values) as well as with a higher infusion rate of 50 pmol/kg·min.

These results could be interpreted in two ways. First, it is possible that GLP-1 and its receptor are not involved in the function of the glucose sensor. Second, fasting GLP-1 is?
levels may be sufficient to activate the receptor to confer maximal sensitivity of the hepatoportal sensor to glucose. To discriminate between these two possibilities, exendin-(9-39) was coinfused with glucose into the hepatoportal vein. Strikingly, this led to a strong inhibition of the portal sensor, as revealed by the suppression of both the hypoglycemia-inducing effect and the increased glucose clearance. This effect was already at maximum, with a rate of

FIG. 3. Exendin-(9-39) prevents activation of the hepatoportal glucose sensor. Glucose was infused at a rate of 25 mg/kg · min and exendin-(9-39) was infused at a rate of 0.5 pmol/kg · min through the portal (P-Ex, △) or the femoral (F-Ex, ○) vein of mice, or glucose was infused into the portal vein and exendin-(9-39) was infused into the femoral vein (P-fEx, ⊙). Data were compared with S-Ex mice (●). A: Glycemic pattern of the infused mice (I). The mean AUC of the blood glucose concentration values relative to the fasting values is also shown (II). Each data point is the mean ± SE for n ≥ 6 for each group. B: Blood glucose clearance rate calculated during the last hour of the infusion. C: Insulinemia during the glucose or saline infusion protocols (I). The mean AUC of the blood glucose concentration values relative to the fasting values is also shown (II). Data are the means ± SE for five to six mice per group. *Statistically different from P-Ex mice; #statistically different from S-Ex mice; P < 0.05.
infusion of 0.5 pmol/kg · min. It could not be explained simply by a decrease in insulin secretion because the insulin AUC over the period of infusion was similar whether exendin-(9-39) was present or absent. To evaluate whether exendin-(9-39) was acting on the portal sensor and not on GLP-1 receptors present on other glucose sensors, we infused glucose through the portal vein and exendin-(9-39) through the femoral vein at the rate of 0.5 pmol/kg · min. We expected that under these conditions, if the peptide was acting on the portal sensor, its infusion...
through the femoral vein would lead to a sufficient dilution of its circulating concentration such that no inhibition of the portal sensor could be obtained. This is indeed what we observed; hypoglycemia and increased glucose clearance rate were not inhibited. Therefore, we conclude that there is a direct effect of exendin-(9-39) on inhibition of the portal vein glucose sensor.

Interestingly, exendin-(9-39), when coinfused with glucose into the portal or the femoral vein, did not reduce plasma insulin concentration, as could have been expected from the antagonist activity of this peptide. However, under these conditions, hyperglycemia developed and may have a dominant effect on the stimulation of insulin secretion.

What is the mechanism by which exendin-(9-39) inhibits the portal glucose sensor? GLP-1 is secreted by L-cells located primarily in the distal small intestine and the colon and is collected into the portal circulation before being distributed to the periphery, including to pancreatic β-cells. Therefore, one can suppose that the portal sensor is exposed to the highest plasma concentration of GLP-1. This may be even more true when we consider that GLP-1 is rapidly inactivated in the plasma by dipeptidylpeptidase IV, an enzyme that is found at particularly high levels in those endothelial cells forming capillaries found in close proximity to L-cells (23). This therefore suggests that degradation of the active peptide may be very rapidly initiated after its secretion but that GLP-1 may be present at a higher concentration in the portal vein than in peripheral blood. Thus, even in the fasted state, there may be a sufficient concentration of intact GLP-1 that reaches the portal sensor to maintain it in a maximally glucose-competent state. Exendin-(9-39) would then act by displacing the peptide from its receptor. An alternative explanation may be derived from our previous studies, which demonstrated that in β-cells, the GLP-1 receptor had a basal ligand-free activity and that exendin-(9-39) acted as an inverse agonist, decreasing basal cAMP levels and glucose-stimulated insulin secretion (27). We can therefore propose that exendin-(9-39) may also act as an inverse agonist, reducing the activity of the ligand-free receptor present in the glucose sensor.

Interestingly, the P–GLP-1 and P-mice had similar glucose clearance rates, but the former group had a higher plasma insulin level, suggesting that either the small rise in insulin had no consequence on the glucose clearance or that insulin resistance was activated by portal GLP-1 infusion. Similarly, previous data (24) showed that an intraportal injection of a small dose of GLP-1 could increase insulin secretion, an effect not observed when the same dose of GLP-1 was injected through the jugular vein. However, despite these different insulinemic levels, the glycemic patterns were the same with or without GLP-1 injection, also suggesting that insulin-induced glucose clearance was reduced by GLP-1 injection.

The observation that the GLP-1 receptor was involved in the control of the hepatoporal glucose sensor was further investigated in GLP-1R−/− mice. We showed that portal glucose infusion failed to activate glucose clearance and that it also failed to induce hypoglycemia. Because these mice have a general inactivation of the receptor, which also potentiates insulin secretion, it was critical to evaluate the insulin profiles during the time course of the experiment. Our data show that basal insulinemia of the fasted mutant mice was higher than that of control mice. In addition, portal or femoral glucose infusion increased plasma insulin to similar levels above those of the saline-infused mutant mice. However, activation of glucose clearance and induction of hypoglycemia were no longer detectable after stimulation of the glucose sensor by glucose. We therefore take these observations as a further indication that the activation of the hepatoporal sensor requires expression of the GLP-1 receptor.

Our observations indicate that exogenous GLP-1 infusion in the portal vein does not increase glucose clearance. This could suggest that the hepatoporal sensor is not normally modulated by postprandial elevations in GLP-1, which would be in contrast to other reports showing that portal GLP-1 infusion stimulates the sensor. Indeed, activation of the sensor by a portal-peripheral glucose gradient decreases the firing rate of vagal afferents originating from the portal vein (1), and portal infusion of GLP-1 increased this firing rate (22,28). Although these data suggest a modulation of the sensor by GLP-1, the induced change in firing activity is opposite of that change triggered by glucose, indicating that GLP-1 should oppose the glucose effect rather than stimulate it. In contrast, here we find that the effect of glucose was inhibited by the GLP-1 antagonist exendin-(9-39). Furthermore, we previously showed that somatostatin blocked the effect of the activated portal sensor on stimulation of glucose utilization (15), whereas Nakabayashi et al. (22,28) reported that somatostatin increased the firing rate of the afferent branches of the vagal nerve, similar to GLP-1. Thus, whereas these two hormones have opposite effects on glucose clearance, they have the same effect on firing rates. Therefore, the effect of the activated portal sensor may not be transmitted uniquely by the vagal afferences. In this context, our previous data (15) showed that hindlimb denervation only partly prevented the effect of the activated hepatoporal glucose sensor on stimulation of glucose utilization, suggesting that the link between the sensor and target tissues may involve multiple neural mechanisms. Alternatively, the portal glucose sensor may be connected to multiple efferent pathways that control different physiological functions, and these pathways may be activated by distinct GLP-1 concentrations.

Finally, because the hepatoporal glucose sensor shows similarities with the pancreatic β-cells, it can be hypothesized that a defect in glucose sensing by this sensor may also develop in diabetes and accentuate the diabetic syndrome. Because the sensor is activated by a portal-peripheral glucose gradient, diabetic glycaemia may prevent the establishment of this gradient and therefore prevent glucose sensing. Understanding the molecular mechanisms of hepatoporal glucose sensing, signal transduction, and activation of glucose uptake by peripheral tissues may lead to identification of novel therapeutic targets for the treatment of diabetes.

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REFERENCES


