Selective activation of central NPY Y1 vs. Y5 receptor elicits hyperinsulinemia via distinct mechanisms

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METHODS

Animals. Adult male LE rats (250–300 g; Charles River, MA) were housed individually and maintained in a temperature- and light-

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controlled environment on a 12:12 h light-dark cycle (lights on at 4:00 AM). Animals had free access to food and water. All studies were conducted in a facility accredited by the American Association for Accreditation of Laboratory Animal Care. The following protocols were approved by the Schering-Plough Research Institute’s Animal Care and Use Committee according to the guideline of the National Institutes of Health for the care and use of laboratory animals.

**Surgery.** A single 22-gauge stainless steel guide cannula (Plastics One, Roanoke, VA) was chronically implanted in the lateral ventricle of a male Sprague-Dawley rat under ketamine-xylazine (100:10 mg/kg ip) anesthesia by use of the following coordinates: 1.0 mm posterior to bregma, 1.5 mm lateral to midline, and 3.6 mm ventral to dura (16). The cannula was secured to the surface of the skull with jeweler’s screws and dental cement, and a 28-gauge obturator was inserted into the cannula to maintain patency. After a 3-wk recovery period, all animals were tested for cannula placement by central infusion of 0.3 nmol of NPY. Only animals demonstrating a prompt and robust feeding effect (>2.0 g intake within 1 h of infusion) were retained for the study.

**Peptide and infusion protocols.** About 1 wk after the NPY challenge, rats were icv infused with sterile saline during the nadir of the light cycle, and their food intake was monitored for 2 h. Cannulated rats were balanced into six study groups (NPY, Y1, Y2, Y4, Y5, and saline control) on the basis of their NPY-induced food intake and saline baseline. Rats were evenly divided into the “with food” and “without food” paradigms within each study group. Human NPY, rPP, d-Trp34 NPY, d-Arg25 NPY, C2-NPY, and cPP NPY were synthesized by AnaSpec (San Jose, CA). All peptides were dissolved in 0.9% sterile saline (Sigma, St. Louis, MO) and infused icv at 1 nmol, which was the minimal effective dose of d-Trp34 NPY and d-Arg25 NPY on feeding at the 1-h time point (28, 29). Hamilton infusion pumps and syringes (Bioanalytical System, N, Lafayette, IN) were used at a rate of 5 μl/min for 1 min. The infusion cannula remained inserted for an additional minute to prevent diffusion up the needle track. The chew-filled feeder (Purina Rodent Chow no. 5053, St. Louis, MO) was weighed during the infusion period and then returned to the home cage with the animal immediately after treatment. The feeder was not returned to the home cages with animals in the “without food” group. Food consumption was monitored, and blood samples were collected by heart puncture at 15, 60, or 120 min after the 1-min icv infusion. Because the protruding icv cannula may get caught in the wire cage, rats were individually housed in plastic cages with corn cob bedding (bed-o-cobs, 1/4 in.; Anderson Cob Mills, Malumee, OH). Minor powdery food spillage was not recorded, which may potentially overestimate the food intake of the treated groups at the 1-h and 2-h time points. All rats were infused at the nadir of the light cycle, which is ∼6–7 h after lights on. After the study, rat brains were infused with dye, fixed in 10% Formalin saline solution, and sectioned, and injection sites were determined under light microscopy. All rats were killed between 11:00 AM and 12:00 PM (7–8 h after lights on) for blood sample collection after icv infusion (15 min, 1 h, or 2 h). Blood samples were collected into heparinized tubes, and plasma was isolated for assays after centrifugation at 3,000 rpm.

**Plasma insulin, glucagon, and glucose assays.** Both insulin and glucagon were analyzed by ELISA kits from ALPCO Diagnostics (Windham, NH) and Peninsula Laboratories (San Carlos, CA), respectively. The coefficients of variation for insulin and glucagon ELISA assays were 4.9 ± 1.2 and 8.4 ± 1.9%, respectively. Glucose was analyzed by Sigma Diagnostic Glucose Trinder Agent (St. Louis, MO).

**Statistical analysis.** Results are given as means ± SE. For each time point, plasma insulin, glucagon, and glucose levels were compared by two-way ANOVA (peptide treatment × food access). Whenever the overall model was statistically significant, with significant food effects, data were further separated into “with food” vs. “without food” groups and analyzed against the respective saline control groups. When Bartlett’s test indicated that the group comparisons had equal variances, one-way ANOVA and Dunnett’s multiple comparison post hoc tests were used. When the group data showed unequal variances, the nonparametric Wilcoxon/Kruskal-Wallis and Dunn’s multiple comparison post hoc tests were used. Comparisons between the paired groups in the presence or absence of food were analyzed by Student’s t-tests. P < 0.05 was considered to be significant. These statistical tests were performed using JMP 4.0.4 (SAS Institute, Cary, NC) and Prism 3.0 (GraphPad Software, San Diego, CA).

**RESULTS**

Fifteen minutes after icv infusion of saline vs. 1 nmol of NPY or NPY analogs. Central administration of NPY and its analogs did not induce increased food intake (Fig. 1A) or any significant changes in plasma glucagon and glucose levels (Fig. 1, C and D) at the 15-min postinfusion time. However, plasma insulin levels were significantly elevated after icv infusion of the selective Y1 agonist d-Arg25 NPY (1 nmol) compared with the saline control groups [Fig. 1B, two-way ANOVA F(11,59) = 6.02, P < 0.0001]. Kruskal-Wallis and Dunn’s multiple comparison tests showed that the combined Y1 treatment effects, with and without food, were significantly different from control, P < 0.001. In contrast, plasma insulin levels were not significantly different from control with NPY or with NPY analogs that selectively stimulate Y2, Y4, or Y5 receptor subtypes (Fig. 1B).

One hour after icv infusion of saline vs. 1 nmol of NPY or NPY analogs. Central administration of 1 nmol of NPY, the Y1-selective agonist (d-Arg25 NPY), or the Y5-selective agonists (cPP NPY) produced an increase in food intake that was significantly greater than the saline control group 1 h postinfusion (Fig. 1A; Kruskal-Wallis and Dunn’s multiple comparison tests, NPY: P < 0.001, Y1: P < 0.05, Y5: P < 0.01). In the presence of food, icv infusion of NPY, Y1, or Y5 agonists resulted in elevated levels of plasma insulin that were significantly higher than the level of saline control animals [Fig. 2B; two-way ANOVA, F(11,103) = 14.0, P < 0.001; Kruskal-Wallis and Dunn’s multiple comparison tests, NPY: P < 0.01, Y1: P < 0.01, Y5: P < 0.01]. In the absence of food after icv infusion, only the selective Y1 agonist produced increased plasma insulin levels (Fig. 2B, Kruskal-Wallis and Dunn’s multiple comparison tests, Y1: P < 0.01). Moreover, plasma insulin levels induced by icv NPY, Y1, and Y5 agonists in animals with food were significantly higher than those in rats without food (Student’s t-test, P < 0.05; Fig. 2B).

Plasma glucagon levels in Y2 agonist-treated rats were significantly lower than the level in the saline group with or without food 1 h postinfusion [Fig. 2C; two-way ANOVA, F(11,103) = 4.34, P < 0.001; Kruskal-Wallis and Dunn’s multiple comparison tests, with food, P < 0.01; without food, P < 0.05]. However, plasma glucagon levels of all other treatments were not significantly different from control.

In a different group of rats, plasma glucose levels were measured 1 h after icv infusion of these peptides. We did not observe any significant change of plasma glucose levels 1 h after icv infusion (Fig. 2D).

Two hours after icv infusion of saline vs. 1 nmol of NPY or NPY analogs. Rats given NPY, the Y1 agonist (d-Arg25 NPY), or the Y5 agonist (d-Trp34 NPY) consumed significantly more food than the saline control group 2 h after icv infusion [one-way ANOVA, F(5,30) = 11.7, P < 0.0001, with Dunnett’s multiple comparisons posttests, NPY: P < 0.01, Y1: P < 0.01, Y5: P < 0.05; Fig. 3A]. However, only NPY and the Y1-selective agonist (d-Arg25 NPY) induced a significant in-
crease in plasma insulin levels 2 h postinfusion compared with
the saline control group with food [Fig. 3B; two-way ANOVA,
\( F(11,59) = 5.18, P < 0.0001; \) Kruskal-Wallis and Dunn’s
multiple comparison tests with food, NPY: \( P < 0.01; \) Y1: \( P <
0.05 \). In the absence of food, the plasma levels of insulin
remained the same across all groups (Fig. 3B). In the presence
of food, the plasma insulin levels were significantly higher than
without food 2 h after NPY or Y1 agonist infusions (Kruskal-
Wallis and Dunn’s multiple comparison tests with food, NPY:
\( P < 0.01; \) Y1: \( P < 0.01 \), Fig. 3B).

Plasma glucagon levels in NPY-treated groups were signif-
icantly increased in the presence of food [two-way ANOVA,
\( F(11,59) = 3.82, P < 0.001; \) Kruskal-Wallis and Dunn’s
multiple comparison tests with food, NPY: \( P < 0.05 \), Fig. 3C].
In addition, there was a significant difference in NPY-induced
plasma glucagon levels in the presence and absence of food
(ANOVA with Student’s t-test, \( P < 0.05 \), Fig. 3C).

Two hours after icv infusion of the Y1 or Y2 agonist, plasma
glucose levels were significantly decreased compared with
control group in the presence of food [two-way ANOVA,
NPY is an important regulator of energy balance in mammals through its orexigenic, antithermogenic, and hyperinsulinemic actions. The present study is the first to delineate the central NPY receptor subtype(s) involved in the regulation of plasma insulin, glucagon, and glucose levels by the use of selective NPY Y1, Y2, Y4, or Y5 receptor agonists. Our data demonstrate that a selective Y1 agonist, d-Arg25 NPY, induced a significant elevation of plasma insulin levels in satiated rats at all time points measured. d-Arg25 NPY also significantly raised plasma insulin levels in the absence of food 1 h after icv infusion, suggesting that Y1-induced hyperinsulinemia does not completely depend on the ingestion of food. The Y1-induced hyperinsulinemia may contribute to the significantly reduced plasma glucose levels at 2 h after icv infusion with or without food. In contrast, a selective Y5 agonist only increased plasma insulin levels in the presence of food 1 h after icv infusion. The Y5-induced hyperinsulinemia was significantly reduced in the absence of food, indicating that Y5-induced hyperinsulinemia was secondary to the ingestion of food. In addition, our data confirm our previous finding that the selective Y2 agonist C2-NPY and the selective Y4 agonist rPP do not elicit feeding behavior during the nadir of the light cycle. Furthermore, central administration of the selective Y2 agonist significantly reduced plasma glucagon levels with or without food at 1 h postinfusion and decreased plasma glucose levels 2 h postinfusion without food, whereas the Y4 agonist does not have a significant effect on plasma insulin, glucagon, or glucose levels.

Pancreatic insulin and glucagon secretion is a tightly regulated process that maintains energy fuel homeostasis. In addition to the close control of blood glucose levels, the secretion of insulin is in part regulated by the vagus nerve. Activation of the parasympathetic nervous system can stimulate the secretion of insulin (22, 44) and enhance the insulin secretory response to glucose (37). It has been suggested that central administration of NPY may act directly on the nucleus of solitary tract, which may mediate the direct link to the pancreas via a vagal pathway to enhance insulin secretion (10). It has been demonstrated that the muscarinic receptor antagonist atropine or vagotomy can block icv NPY-induced insulin release or gastropancreatic secretion, which may be considered as a cephalic phase of secretion (11, 43). High densities of Y1, Y2, and Y4 NPY receptor subtypes have been reported within the dorsal vagal complex, including nucleus of the solitary tract and dorsal motor nucleus of vagus (3, 18, 21). Recent studies have also indicated that Y1 receptors in the dorsal vagal complex may be involved in NPY-induced bile secretion as well as peptide YY-induced gastric acid secretion (45, 46). Our data suggest that selective activation of the Y1 receptor, but not Y2, Y4, or Y5 receptors, significantly elevated plasma insulin levels independent of food ingestion. Because we administered these peptides by lateral ventricle icv infusion, these peptides may have multiple sites of action in the brain. Therefore, additional studies including fourth ventricle or site-specific injection of NPY or a Y1 selective peptide will be necessary to provide further insight into the role of NPY and the Y1 receptor on insulin response. Alternatively, NPY-induced hyperinsulinemia may be partly caused by decreasing insulin clearance. Obesity and high levels of free fatty acids can reduce insulin clearance by lowering hepatic insulin extraction and inhibiting insulin-degrading enzyme (13, 36, 41). Chronic central infusion of NPY can induce an obesity syndrome, which includes hyperphagia, hyperinsulinemia, hypertriglyceridemia, hypercorticosterenemia, and weight gain in rodents (33). It is known that the proportions of insulin, proinsulin, and conversion intermediates in plasma and pancreas are not affected by chronic central infusion of NPY (33). It is not clear whether acute icv infusion of NPY or its analogs may have any effect on insulin clearance. Hyperinsulinemia induced by central administration of NPY in

DISCUSSION

NPY is an important regulator of energy balance in mammals through its orexigenic, antithermogenic, and hyperinsulinemic actions. The present study is the first to delineate the central NPY receptor subtype(s) involved in the regulation of plasma insulin, glucagon, and glucose levels by the use of selective NPY Y1, Y2, Y4, or Y5 receptor agonists. Our data demonstrate that a selective Y1 agonist, d-Arg25 NPY, induced a significant elevation of plasma insulin levels in satiated rats at all time points measured. d-Arg25 NPY also significantly raised plasma insulin levels in the absence of food 1 h after icv infusion, suggesting that Y1-induced hyperinsulinemia does not completely depend on the ingestion of food. The Y1-induced hyperinsulinemia may contribute to the significantly reduced plasma glucose levels at 2 h after icv infusion with or without food. In contrast, a selective Y5 agonist only increased plasma insulin levels in the presence of food 1 h after icv infusion. The Y5-induced hyperinsulinemia was significantly reduced in the absence of food, indicating that Y5-induced hyperinsulinemia was secondary to the ingestion of food. In addition, our data confirm our previous finding that the selective Y2 agonist C2-NPY and the selective Y4 agonist rPP do not elicit feeding behavior during the nadir of the light cycle. Furthermore, central administration of the selective Y2 agonist significantly reduced plasma glucagon levels with or without food at 1 h postinfusion and decreased plasma glucose levels 2 h postinfusion without food, whereas the Y4 agonist does not have a significant effect on plasma insulin, glucagon, or glucose levels.

Pancreatic insulin and glucagon secretion is a tightly regulated process that maintains energy fuel homeostasis. In addition to the close control of blood glucose levels, the secretion of insulin is in part regulated by the vagus nerve. Activation of the parasympathetic nervous system can stimulate the secretion of insulin (22, 44) and enhance the insulin secretory response to glucose (37). It has been suggested that central administration of NPY may act directly on the nucleus of solitary tract, which may mediate the direct link to the pancreas via a vagal pathway to enhance insulin secretion (10). It has been demonstrated that the muscarinic receptor antagonist atropine or vagotomy can block icv NPY-induced insulin release or gastropancreatic secretion, which may be considered as a cephalic phase of secretion (11, 43). High densities of Y1, Y2, and Y4 NPY receptor subtypes have been reported within the dorsal vagal complex, including nucleus of the solitary tract and dorsal motor nucleus of vagus (3, 18, 21). Recent studies have also indicated that Y1 receptors in the dorsal vagal complex may be involved in NPY-induced bile secretion as well as peptide YY-induced gastric acid secretion (45, 46). Our data suggest that selective activation of the Y1 receptor, but not Y2, Y4, or Y5 receptors, significantly elevated plasma insulin levels independent of food ingestion. Because we administered these peptides by lateral ventricle icv infusion, these peptides may have multiple sites of action in the brain. Therefore, additional studies including fourth ventricle or site-specific injection of NPY or a Y1 selective peptide will be necessary to provide further insight into the role of NPY and the Y1 receptor on insulin response. Alternatively, NPY-induced hyperinsulinemia may be partly caused by decreasing insulin clearance. Obesity and high levels of free fatty acids can reduce insulin clearance by lowering hepatic insulin extraction and inhibiting insulin-degrading enzyme (13, 36, 41). Chronic central infusion of NPY can induce an obesity syndrome, which includes hyperphagia, hyperinsulinemia, hypertriglyceridemia, hypercorticosterenemia, and weight gain in rodents (33). It is known that the proportions of insulin, proinsulin, and conversion intermediates in plasma and pancreas are not affected by chronic central infusion of NPY (33). It is not clear whether acute icv infusion of NPY or its analogs may have any effect on insulin clearance. Hyperinsulinemia induced by central administration of NPY in

$F(11,59) = 2.74, P < 0.01; \text{with Dunnett’s multiple comparisons posttests, } P < 0.05, \text{Fig. } 3D\}.$

Fig. 3. Two hours after treatments, effects of icv injection of saline, and of 1 nmol of NPY, Y1 (d-Arg25 NPY), Y2 (C2-NPY), Y4 (rPP), and Y5 (d-Trp34 NPY) agonists on food intake (A) and plasma levels of insulin (B), glucagon (C), and glucose (D) were measured. Values are means ± SE; nos. of rats are shown inside bars. *$P < 0.05$ vs. with food of same peptide treatment.
rats can be prevented by adrenalectomy, a surgery that eliminates glucocorticoid production in the adrenal gland. This effect was associated with a concomitant reduction in Y1 and Y5 receptor mRNA expression in the ventral medial hypothalamus (43). Glucocorticoids may have a direct effect in controlling insulin release via NPY-regulated pathways, since the Y1 receptor gene is known to have a putative glucocorticoid response element (2).

In addition to the centrally mediated hyperinsulinemic effect of NPY, it has been known that NPY regulates insulin secretion by a peripheral mechanism. NPY can inhibit insulin secretion when given intravenously or when applied directly to isolated pancreatic islets (31, 40). Expression of the Y1 receptor, but not the Y5 receptor, has been detected in Langerhans islet cells (27). The Y1 receptor antagonist BIBP3226 has been shown to block NPY-induced inhibition of insulin secretion via a Gt-mediated inhibition of adenyl cyclase in RIN 5AH rat insulinoma cells (27). The divergent central vs. peripheral effects of NPY on insulin secretion suggest that the passage of exogenous NPY to venous blood via its bulk and glucose turnover rate in fasting NPY Y1-deficient mice also confirm the tonic role of the peripheral Y1 receptor in plasma insulin regulation (6).

Central administration of NPY has a number of effects on glucose metabolism. In addition to NPY-induced hyperinsulinemia, NPY also increases hepatic glucose output (42), stimulates glucose turnover (23), and changes peripheral tissue responsiveness to insulin (48). The opposing effects of increasing hepatic glucose output and stimulating glucose turnover may partly explain why we did not observe significant changes in plasma glucose levels at 15 or 60 min postinfusion. These data were consistent with literature reports that plasma glucose levels did not change within 90 min after acute NPY infusion in nondiabetic animals (42). However, we have noticed a reduction in plasma glucose levels and an increase in plasma glucagon levels after NPY infusion at the 2-h time point. Because one of the physiological functions of glucagon is to counter hypoglycemia, it is likely that the increase in glucagon levels was not directly induced by receptor activation but was triggered by the decrease in plasma glucose levels. Alternatively, central infusion of NPY has been shown to increase glucagon secretion in the hyperinsulinemic euglycemic clamp, suggesting that a direct effect of icv NPY on glucagon secretion is possible (42).

Although hypothalamic Y1 and Y5 receptors are both involved in icv NPY-induced hyperphagia and hyperinsulinemia, our data suggest that the mechanisms by which these receptors regulate insulin secretion may not be the same. Y1 agonist-induced hyperinsulinemia was not solely dependent on food intake, whereas Y5 agonist-induced hyperinsulinemia was dependent on food ingestion. In addition, plasma glucose levels were significantly reduced by central infusion of the Y1 agonist, but not the Y5 agonist. In summary, central administration of NPY and its analogs could stimulate insulin release through activation of Y1 or Y5, but not Y2 or Y4, receptors. Our data suggest that selective activation of the central Y1 receptors can induce hyperinsulinemia independently of food, whereas the Y5-mediated hyperinsulinemia is dependent on food ingestion.

REFERENCES


