The CNS glucagon-like peptide-2 receptor in the control of energy balance and glucose homeostasis

Xinfu Guan

U.S. Department of Agriculture/Agricultural Research Service, Children’s Nutrition Research Center, Department of Pediatrics; and Division of Diabetes, Endocrinology and Metabolism, Department of Medicine, Baylor College of Medicine, Houston, Texas

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Guan X. The CNS glucagon-like peptide-2 receptor in the control of energy balance and glucose homeostasis. Am J Physiol Regul Integr Comp Physiol 307: R585–R596, 2014. First published July 2, 2014; doi:10.1152/ajpregu.00096.2014.—The gut-brain axis plays a key role in the control of energy balance and glucose homeostasis. In response to luminal stimulation of macronutrients and microbiota-derived metabolites (secondary bile acids and short chain fatty acids), glucagon-like peptides (GLP-1 and -2) are cosecreted from endocrine L cells in the gut and coreleased from preproglucagoneric neurons in the brain stem. Glucagon-like peptides are proposed as key mediators for bariatric surgery-improved glycemic control and energy balance. Little is known about the GLP-2 receptor (Glp2r)-mediated physiological roles in the control of food intake and glucose homeostasis, yet Glp1r has been studied extensively. This review will highlight the physiological relevance of the central nervous system (CNS) Glp2r in the control of energy balance and glucose homeostasis and focuses on cellular mechanisms underlying the CNS Glp2r-mediated neural circuitry and intracellular PI3K signaling pathway. New evidence (obtained from Glp2r tissue-specific KO mice) indicates that the Glp2r in POMC neurons is essential for suppressing feeding behavior, gastrointestinal motility, and hepatic glucose production. Mice with Glp2r deletion selectively in POMC neurons exhibit hyperphagic behavior, accelerated gastric emptying, glucose intolerance, and hepatic insulin resistance. GLP-2 differentially modulates postsynaptic membrane excitability of hypothalamic POMC neurons in Glp2r- and PI3K-dependent manners. GLP-2 activates the PI3K-Akt-FoxO1 signaling pathway in POMC neurons by Glp2r-p85α interaction. Intracerebroventricular GLP-2 augments glucose tolerance, suppresses glucose production, and enhances insulin sensitivity, which require PI3K (p110α) activation in POMC neurons. Thus, the CNS Glp2r plays a physiological role in the control of food intake and glucose homeostasis. This review will also discuss key questions for future studies.

glucagon-like peptides; glucose homeostasis; food intake; gastric emptying; gut-brain axis; insulin sensitivity; central nervous system surgery (particularly, Roux-en-Y gastric bypass, RYGB) has proven to be the most effective therapy for morbid obesity and diabetes (19, 26, 111), in which the gut-brain axis is highly involved in mediating beneficial effects on food intake, glycemic control, and weight loss.

The gut-brain axis (i.e., the bidirectional communication between the gut and the brain) plays key roles in the regulation of energy and glucose homeostasis. Gut-derived signals (for nutritional, neural, immune, and endocrine information) are input from the gut to the brain; meanwhile, autonomic and neuroendocrine messengers are output from the brain to the gut. The hypothalamus, a primary region of central integration for homeostatic signals, plays crucial roles in the regulation of energy balance and glucose homeostasis (7, 104, 114). In the arcuate nucleus (ARC) of the hypothalamus, neurons expressing proopiomelanocortin (POMC), a key component of the central melanocortin system, are positioned to integrate hormonal/nutritional signals reflecting energy availability (25). Activation of POMC neurons enhances energy expenditure and suppresses food intake, yet neuroendocrine mechanisms are not fully established. The gastrointestinal (GI) tract plays a critical role in digestion, absorption, and utilization of nutrients (32), thus, controlling energy intake at the first pass. Through the gut-brain axis, gut hormones play a crucial role in the regulation of energy balance (including food intake) and glucose homeostasis (27, 50). Recently, it has been shown that infusion of glucose or lipid into the rat jejunum improves glucose homeostasis in uncontrolled diabetes, suggesting that nutrient sensing by the gut-brain axis may play a key role in the control of glucose production (14, 31), yet little is known about the nutrient sensor identity and intracellular signaling network.

In response to luminal stimulation of macronutrients and microbiota-derived metabolites (secondary bile acids and short-chain fatty acids), glucagon-like peptides (GLP-1 and GLP-2) are cosecreted from endocrine L cells in the gut (59, 100, 102, 106, 108, 123, 124) and are presumably coreleased from preproglucagonergic (PPG) neurons in the brain stem as well. GLP-1 and GLP-2 are key neuroendocrine signals for the gut-brain axis to control food intake and glucose homeostasis (92) and have been proposed as important mediators for bariatric surgery-improved glycemic control and insulin sensitivity (37, 47, 73, 74, 99, 121). In fact, GLP-1 and -2 receptor agonists are used clinically for the prevention and treatment of diabetes and digestive diseases (92). By means of neural and endocrine

AMONG THE GREATEST THREATS to public health are increasing rates of obesity and diabetes. Obesity promotes the development of more than 50 chronic disorders and costs ~9% of all U.S. health care expenditures (22). Thus, it is imperative to identify novel therapeutic targets and develop effective approaches to prevent and treat obesity and diabetes. Bariatric
pathways, gut-derived GLP-1 and -2 signals are transduced to
the brain to coordinate food intake and glucose homeostasis
(14, 130), although their physiological roles are largely un-
known. Thus, elucidation of GLP-1 and -2 intracellular signal-
ing and metabolic action in the control of energy balance may
reveal novel targets for the treatment of intestinal dysfunctions,
obesity, and diabetes (92).

Through acting on a specific G protein-coupled receptor
(GLp2r), GLP-2 promotes intestinal epithelial homeostasis and
function, enhances intestinal nutrient absorption and blood
flow, assists gut immune defense, and improves outcomes of
short bowel syndrome (9, 47, 57). Except for its enterotrophic
role, GLP-2-mediated metabolic action has not been fully
recognized. Without the incretin effect, GLP-2 was considered
insignificant in glucose homeostasis. Recent studies reveal that
central infusion of GLP-2 suppresses food intake and increases
glucose tolerance (118, 121, 122). Importantly, GLP-2 has
been proposed as a neurotransmitter in the control of feeding
behavior (121, 122) and may mediate PPG neuron-induced
synaptic transmission linking the hypothalamus and the brain
stem (121). The GLP-2 receptor (GLp2r) is not only expressed
in nutrient-sensing endocrine cells (such as enteroendocrine
cells and pancreatic ß-cells), but also neurons (such as enteric
neurons, vagal sensory neurons, and central neurons) (30, 45,
91, 95, 131, 138), suggesting complex modes for GLP-2 action
via endocrine, paracrine, or neuroendocrine mechanisms. Thus,
GLP-2 may act as a crucial neuroendocrine signal (for tempo-
rary energy availability) to the hypothalamus in the control of
feeding behavior (food intake) and glucose homeostasis. It
seems that bariatric surgery-improved glucose tolerance is
independent of GLp1r activation in rodents (85, 133, 136).
Notably, bariatric surgery not only improves glucose toler-
ance, but also restores insulin sensitivity. GLp2r/GLp1r (two
G protein-coupled receptors) play distinct roles, yet GLP-1
and GLP-2 are cosecreted. GLp2r and GLp1r in postprandial
glycemic control have not been determined. Thus, it is still
crucial to determine whether GLp2r is a key contributor to
improving glycemic control and insulin sensitivity after
bariatric surgery.

To decode its physiological role and signaling path-
way, my laboratory has generated a GLp2r floxed mouse line
that has provided a powerful, genetic tool to dissect GLP-2
metabolic and mitogenic actions in a tissue (or cell)-specific
manner. Using GLp2r tissue-specific knockout mouse models,
Guan et al. show that GLp2r is a key satiety signal for the
physiological control of food intake and gastric emptying, and
this may contribute to the homeostatic control of energy
balance and body weight (46). Moreover, GLp2r in hypo-
thalamus POMC neurons is required for promoting hepatic insulin
sensitivity and glycemic control (118). Through the gut-brain-
stem/stomach (or -liver) axis, GLP-2 plays key physiological roles
in the control of gastric emptying and hepatic glucose produc-
tion (HGP) (46, 118). In this review, we will focus on the
physiological significance and cellular action of the central
nervous system (CNS) GLP-2 in the control of feeding
behavior and glucose homeostasis and propose that GLP-2
as an endocrine and neural signal may transmit intestinal
nutrient sensing to the hypothalamus-brain stem to suppress
feeding behavior and glucose production in a negative-
feedback manner.

GLP-2R Is Expressed in the Hypothalamus and Brain Stem

The rodent GLp2r mRNA is not only expressed in the
hypothalamic [dorsomedial nucleus of the hypothalamus
(DMH) and ARC], but also localized in the hippocampus and
the brain stem (DMV and PBN) (81, 121, 131). Using fluo-
rescence in situ hybridization and immunohistochemistry [us-
ing validated GLp2r antibody(45)], we further confirmed that
GLp2r mRNA and protein are expressed in neurons in the ARC
and DMH, as reported previously (118, 121). Moreover, the
GLp2r protein is expressed in the POMC neurons (118). Intra-
cerebroventricular infusion of GLP-2 increases POMC mRNA
expression in the mouse ARC region (46). These data suggest
that GLp2r in POMC neurons may play an important, physio-
logical role in the control of feeding behavior and glucose
homeostasis.

CNS GLp2r Suppresses Feeding Behavior

Is the CNS GLP-2 a key satiety signal for the physiological
short-term control of feeding behavior? It was debated that
intracerebroventricular GLP-2 suppresses food intake, but pe-
ripheral GLP-2 does not (80, 121, 122). The hypothalamus
plays pivotal roles in the regulation of energy balance and
epilepsy and metabolic action in the control of energy balance may
be considered insignificant in glucose homeostasis. Recent studies reveal that
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feeding behavior and glucose production in a negative-
feedback manner.
CNS Glp2r Decelerates In Vivo Gastric Emptying

Gastrointestinal motility is fine-tuned by metabolic, neuronal, and hormonal signals and plays a crucial role in the control of digestion and absorption, influencing the intake rate of net energy. Specifically, gastric emptying is a critical process for the short-term control of food intake and perhaps contributes to the long-term maintenance of energy homeostasis (46, 86, 134, 141). Gastric emptying is enhanced with overeating (34) and obesity (18, 134). The overall impact of faster gastric emptying results in shorter satiety period, increasing meal frequency, and energy intake (56). Thus, gastric emptying may be a target for controlling appetite (34, 56).

Peripheral GLP-2 induced the gastric relaxation in vitro in rodents (3) but showed inconsistent gastric emptying in humans (93). Glp2r is expressed in both excitatory and inhibitory enteric neurons (24, 45). Thus, peripheral GLP-2 inhibits the gastrointestinal motility by decreasing cholinergic neurotransmission and/or increasing nitric oxide or vasoactive intestinal peptide release (2, 4). Little was known about the physiological relevance of the CNS GLP-2 in the regulation of gastric emptying. To determine whether Glp2r in POMC neurons modulates gastric motility to control intake of net energy, we quantified the mouse gastric emptying under the conscious condition using $^{13}$C-octanoic acid breath test (46). Both half-excretion time ($T_{1/2}$) and lag phase ($T_{lag}$) for liquid meal were dramatically shorter, while gastric emptying coefficient was higher in the POMC-Glp2r KO mice than those in the WT mice. Thus, the new evidence that Glp2r deletion in POMC neurons accelerated rates of gastric emptying not only explains the hyperphagic behavior, but also supports the notion of ileal break that GLP-1/2 secreted from the endocrine L cells in the ileum slow down gastric emptying to suppress food intake, at least in part, via the gut-brain-stomach axis. Moreover, the Mc4r signaling is required for intracerebroventricular GLP-2-mediated suppression of both food intake and gastric emptying (46). Inhibition of Mc4r-positive cholinergic neurons in the dorsal motor nucleus of the vagus (DMV) would alleviate excitatory input to the gastrointestinal tract, decreasing gastric emptying (42, 110). The CNS Mc4r signaling is important for the tonic control of gastric emptying. Further studies are warranted to determine whether GLP-2 acts on Mc4r-positive neurons in the brain stem through presynaptic input (from POMC-neurons in the NTS) and whether Glp2r deletion in POMC neurons impairs nutrient absorption by the gut per se.

CNS Glp2r Promotes Postprandial Glycemic Control and Hepatic Insulin Sensitivity

Increased hepatic glucose production (HGP; mainly gluconeogenesis) is a major factor in the pathogenesis of hyperglycemia in Type 2 diabetes. GLP-1/2 signals are proposed to contribute to improving metabolic outcomes (including glycemic control and insulin sensitivity) after gastric bypass surgery (37, 73, 74), which may be mediated via a neuroendocrine mechanism instead of incretin action. Except for pancreatic islets, the brain regulates glucose homeostasis (115). Direct action of insulin and leptin on POMC neurons is required to maintain glucose homeostasis via the control of HGP (52, 76, 96, 135). Except for insulin action in the liver, HGP is also suppressed by enhanced hepatic vagal input (43, 67, 71, 98, 105). Moreover, leptin signaling in POMC neurons is sufficient to correct diabetes in Lepr<sup>db/db</sup> mice (58), while insulin receptor (InsR) activation in POMC neurons promotes HGP (76, 96), pointing to the central control of POMC neurons in glucose homeostasis.

Peripheral GLP-2 regulates glucose homeostasis through promoting intestinal absorption of glucose and pancreatic secretion of glucagon (47, 83). Because of its enterotrophic action, GLP-2 is highlighted as a key signal to drive intestinal reprogramming of glucose metabolism to contribute to glycemic improvement after RYGB (113). The CNS GLP-2, like insulin and leptin, may play a crucial role in the control of glucose homeostasis and insulin sensitivity (i.e., suppressing HGP) via enhanced hepatic vagal input (43, 67, 98, 105). Glp2r global deficiency shows severer hyperglycemia and impaired glucose tolerance in Lepr<sup>ob/ob</sup> mice (8), suggesting that Glp2r activation is required for glucose homeostasis in obese mice (8). Leptin can stimulate GLP-1 and -2 secretion from L cells (5). Leptin directly depolarizes PPG neurons in the brain stem (55), suggesting that the CNS GLP may act as key downstream neurotransmitters of the brain stem leptin receptor (LeprR) in the control of food intake and glucose homeostasis. PPG neurons innervate primarily autonomic regions (including hypothalamic ARC, DMH, and PVN; and brain stem DMV) where Glp2r is expressed (46, 77, 118, 121). Our recent data indicate that Glp2r is required for postprandial glycemic control. It is difficult to interpret these data since Glp2r is expressed not only in endocrine cells (such as enterendocrine cells and pancreatic α-cells), but also in neurons (such as enteric neurons, vagal sensory neurons, and the CNS neurons) (45, 131). To dissect the physiological relevance of tissue-specific Glp2r in glycemic control, a site-specific inducible Glp2r knockout mouse model is greatly needed. As Shi et al. have reported (118), mice lacking Glp2r selectively in POMC neurons display impaired postprandial glucose tolerance and hepatic insulin resistance (by increased gluconeogenesis). Intracerebroventricular infusion of GLP-2 increases glucose tolerance and insulin sensitivity, and this requires Glp2r activation in POMC neurons (118), pointing to the physiological significance of GLP-2 neural action in glycemic control. Considering 50% of glycemic control through insulin-independent mechanisms (115), it will be important to quantify the extent to which GLP-2 can distinctly normalize glycemia under insulin and leptin resistance.

Glp2r deletion in POMC neurons impairs postprandial glycemic control and hepatic insulin sensitivity. POMC-Glp2r KO mice display postprandial hyperglycemia and glucose intolerance after intravenous glucose tolerance test (118). Using hyperinsulinemic euglycemic clamp coupled with stable isotopic tracers ($^{1}$H$_{2}$O and 6.6-$^{2}$H$_{2}$glucose), the author’s laboratory has demonstrated that POMC-Glp2r KO mice had lower glucose infusion rate (representing whole body insulin sensitivity), which was attributed mainly to higher HGP and gluconeogenesis since glucose disappearance rate (representing glucose disposal) was not altered. Thus, Glp2r deletion in POMC neurons leads to hepatic insulin resistance, suggesting that Glp2r in POMC neurons is required for insulin-mediated suppression of HGP (i.e., gluconeogenesis). It is noted that glucose tolerance and insulin sensitivity are reduced in obesity. To avoid any confounding effects of body fat mass, glucose tolerance test, and hyperinsulinemic euglycemic clamp were performed in mice at the age of 12 wk (i.e., prior to the onset...
GLP-2 Differentially Modulates the Excitability of POMC Neurons in Glp2r- and PI3K-Dependent Manners

GLP-2 modulates the excitability of two subgroups of POMC neurons differentially. GLP-2 acutely potentiates L-type, voltage-gated Ca\(^{2+}\) (Cav) channel activity in primary hippocampal neurons (131). Although Glp2r is expressed in POMC neurons (46), it was unknown whether GLP-2 can directly modulate their excitability. To determine the GLP-2-induced action on POMC neuronal excitability, we performed whole cell patch-clamp recording on green fluorescent protein (GFP)-labeled POMC neurons in brain slices from POMC-Glp2r KO and WT mice (118). There are two subgroups of hypothalamic POMC neurons in response to acute GLP-2 (118), i.e., GLP-2 (100 nM) acutely depolarized ~50% of POMC neurons with increased spontaneous firing rate; in contrast, GLP-2 (100 nM) acutely hyperpolarized ~50% of POMC neurons with decreased spontaneous firing rate. Of note, leptin-responsive POMC neurons (i.e., acutely activated by leptin) are segregated from insulin-responsive POMC neurons (i.e., acutely inhibited by insulin) (132). In agreement with this new notion, we further identified that GLP-2-excited POMC neurons expressed leptin receptor (Lepr), while GLP-2-inhibited POMC neurons expressed insulin receptor (Insr) by single-cell RT-PCR (118). Currently, little is known about segregated subgroups of hypothalamic POMC neurons (such as neuronal signature, spatial projection, and synaptic transmission, and distinct neural function and metabolic phenotype) in the control of energy balance and glucose homeostasis. It will be important to characterize GLP-2 differentially activated subgroups of POMC neurons, which will ultimately determine their distinct neuroendocrine actions.

GLP-2 modulates the excitability of POMC neurons in Glp2r- and PI3K-dependent manners. Moreover, activation of Glp2r or PI3K is required to modulate the membrane excitability of POMC neurons (118). As shown, GLP-2 neither depolarized nor hyperpolarized POMC neurons with Glp2r deletion in the brain slices, indicating GLP-2 direct action on membrane potential (not attributable to synaptic transmission). Activation of PI3K signaling in POMC neurons is crucial for energy and glucose homeostasis (1, 52, 54, 67, 88, 103) and is required for leptin and insulin to activate transient receptor potential canonical (TRPC) and Kir6.2 KATP channels, respectively, resulting in depolarization and hyperpolarization of POMC neurons to suppress food intake and HGP (11, 53, 68, 103, 119). The PI3K-Akt signaling pathway (as a conserved central node) may underlie GLP-2-modulated membrane excitability. In the presence of PI3K inhibitor, POMC neurons do not respond to GLP-2 anymore. Interestingly, both leptin and insulin activate PI3K signaling in POMC neurons, resulting in depolarization (leptin) or hyperpolarization (insulin). In summary, GLP-2 directly modulates postsynaptic membrane excitability of POMC neurons in Glp2r- and PI3K-dependent manners, and this may be synchronized with leptin and insulin signaling in segregated subgroups of POMC neurons.

Putative ion channels underlying GLP-2 neural action. It is unknown through which ion channels GLP-2 modulates membrane excitability of POMC neurons. Activation of PI3K-Akt signaling pathway potentiates L-type, voltage-dependent calcium channel (Ca\(^{2+}\)) activation and enhances Ca\(^{2+}\) currents in neurons (13, 21, 126). In addition, leptin (via the PI3K signaling) evokes L-type Ca\(^{2+}\) currents (129) and TRPC currents in POMC neurons (107), exciting them. As discussed below, GLP-2 activates the PI3K signaling in POMC neurons (118). Moreover, Glp2r interacts in vitro with calmodulin (82), a protein partner with TRPC channels (96). Using the whole cell patch clamp, Wang and Guan (131) showed that GLP-2 acutely inhibits inward Ca\(^{2+}\) currents (i.e., increases intracellular Ca\(^{2+}\) level) through enhancing L-type, Ca\(^{2+}\) channel activity in primary hippocampal neurons. It will be important to identify whether putative ion channels (Ca\(^{2+}\) and TRPC) are required for GLP-2 to excite Lepr-expressing POMC neurons. ATP-sensitive K\(^{+}\) (K\(_{ATP}\)) channels in the hypothalamus are essential for glucose homeostasis (84). Activation of K\(_{ATP}\) channels in hypothalamic neurons is required for insulin- and leptin-mediated suppression of HGP (97, 98, 104, 120). Insulin-activated PI3K signaling (through PI3P) activates the Sur1/Kir6.2 K\(_{ATP}\) channels in POMC neurons to decrease HGP (1, 60, 70, 98, 103, 104). Thus, we hypothesized that GLP-2 acutely enhances K\(_{ATP}\) channel activity, inhibiting Insr-expressing POMC neurons. A pharmacological study indicates that K\(_{ATP}\) channel activation is responsible for GLP-2-induced inhibition of POMC neurons (118).

In summary, GLP-2 directly modulates postsynaptic membrane excitability of POMC neurons in Glp2r- and PI3K-dependent manners. GLP-2 differentially depolarizes or hyperpolarizes POMC neurons in the hypothalamus, and this paradoxical action may be synchronized with leptin and insulin signaling in segregated subgroups of POMC neurons. Moreover, K\(_{ATP}\) channel activation is responsible for GLP-2-induced inhibition of POMC neurons expressing Insr (118). Studies are warranted to characterize neural and metabolic phenotypes of functionally segregated POMC neurons and to identify putative ion channels underlying GLP-2R-mediated excitation of POMC neurons expressing Lepr.
GLP-2R-Activated Intracellular Signaling Pathways in the Brain

How does GLP-2 act on ARC POMC neurons intracellularly? Little is known about how Glp2r activates intracellular signaling pathways in neurons or endocrine cells. In Glp2r-expressing cells, GLP-2 activates PI3K and PKA signaling pathways (17, 33, 75, 117, 118, 131, 137). The PI3K-Akt signaling pathway in hypothalamic neurons plays a critical role in the control of energy balance and glucose homeostasis (88, 103). Increased PI3K activity in POMC neurons improves insulin sensitivity, whereas decreased PI3K activity impairs HGP (54). As the PI3K major catalytic subunit (38, 61, 66), p110α is required for leptin- and insulin-induced PI3K activity in the hypothalamus (38, 67). Specifically, PI3K signaling in POMC neurons is essential for leptin-induced activation and insulin-induced inhibition of POMC neurons (1, 53). PI3K signaling is required for leptin and insulin to activate TRPC and K<sub>ATP</sub> channels, respectively, resulting in depolarization and hyperpolarization of segregated POMC neurons to suppress food intake and glucose production. We proposed that GLP-2-activated intracellular signaling pathways are cell-specific, i.e., PI3K-dependent Glp2r action in POMC neurons.

GLP-2 activates PI3K signaling by initiating Glp2r-p85α binding. Through Glp2r primary sequence analysis, we noticed a putative p85α-binding motif in the Glp2r amino acid sequence. It has been shown using immunoprecipitation that Glp2r interacts with the PI3K regulatory subunit (p85α) in primary hippocampal neurons (118). This Glp2r-p85α interaction was further confirmed in HEK293 cells transfected with Glp2r-c-myc and p85α-GFP using antibodies against c-myc and GFP. Moreover, Glp2r is required for the basal level of Akt phosphorylation in POMC neurons (118).

GLP-2 activates PI3K-Akt-FoxO1 signaling in POMC neurons. FoxO1 is a downstream target of the PI3K/Akt signaling pathway and regulates energy balance (62, 65). The FoxO1 signaling pathway in hypothalamic neurons is summarized in Fig. 1. It appears that GLP-2 increases Akt phosphorylation at Thr-308 (which requires the intact p85α subunit of PI3K)-dependent manner. However, these results do not necessarily point to GLP-2-mediated, direct phosphorylation on Akt or FoxO1 per se. Interestingly, brain stem Glp1r-mediated suppression of food intake requires a PI3K-dependent decrease in phosphorylation of membrane-bound Akt (112). Therefore, GLP-2 activates the PI3K-Akt-FoxO1 signaling pathway via initiating an interaction of Glp2r and p85α. However, it is still unknown whether GLP-2 induces PI3K-independent phosphorylation of Akt or FoxO1.

PI3K in POMC neurons is required for GLP-2 to promote glucose homeostasis and insulin sensitivity. It appears that GLP-2 acts on POMC neurons through activating the PI3K-Akt-FoxO1 signaling pathway. Is the PI3K activation required for the CNS GLP-2 metabolic action? As a major catalytic subunit of PI3K, p110α is required for leptin- and insulin-induced PI3K activity in the hypothalamus (38, 61, 66). Thus, we generated POMC-p110α KO mice to address this question. Intracerebroventricular GLP-2 promotes insulin sensitivity and glycemic control (indicated by increased glucose tolerance and suppressed basal HGP), and this was abolished in mice with p110α deletion selectively in POMC neurons.

In summary, three lines of evidence indicate that GLP-2 activates the PI3K-Akt-FoxO1 signaling in POMC neurons: 1) Glp2r physically binds to p85α (a PI3K regulator subunit), enhances Akt phosphorylation, and activates PI3K-Akt-dependent nuclear exclusion of FoxO1 in POMC neurons (118). Moreover, GLP-2 rapidly activates the PI3K-Akt-mTOR pathway in primary hippocampal neurons (117). 2) PI3K signaling is required for GLP-2-mediated membrane excitation of POMC neurons (as discussed above). Of note, leptin excites POMC neurons via activation of TRPC channels in a PI3K-dependent manner (53, 88, 89). 3) p110α (a PI3K catalytic subunit) in POMC neurons is required for GLP-2-mediated glycemic control and insulin sensitivity (118). Thus, the CNS GLP-2 plays a key role in the control of HGP via PI3K-dependent activation and nuclear transcription of POMC neurons. We speculate that Glp2r activation → POMC neuronal excitation (via PI3K-dependent activation of TRPC channels) → α-MSH release (as a slow-acting neurotransmitter) on postsynaptic Mc4r-expressing autonomic neurons → glycemic control, Glp2r-induced intracellular signaling in hypothalamic POMC neurons is summarized in Fig. 1.

Key Questions Need To Be Addressed in Future Studies

Are the NTS/DMV direct targets for GLP-2-mediated control of autonomic outflow? Selective activation of distinct neurons in the DVC decreases HGP (mainly gluconeogenesis) (105, 142). As an integrative center from ascending and descending signals, the NTS via postsynaptic GABA/glutamate modulates the DMV that fine-tunes the autonomic outflow to discrete visceral areas (6, 29, 41). Importantly, NTS PPG neurons project widely to key central autonomic sites, including the brain stem and hypothalamus (77, 78, 127), suggesting a potential role of downstream GLP-1/2 receptor signaling in the control of autonomic outputs (79). Specifically, PPG neurons innervate brain stem autonomic neurons, including the dorsal motor nucleus of the vagus (DMV), where Glp2r is expressed (unpublished data) (77). Leptin directly excites PPG neurons (55), suggesting that GLP-1 and -2 may serve as downstream neurotransmitters for brain leptin action and relay vagal afferent signals. GLP-2 indirectly activates the NTS...
neurons through vagal afferents (95). We speculate that GLP-2 secretion (from enteroendocrine L cells) → Glp2r activation on vagal sensory neurons → presynaptic input to PPG neurons in the brain NTS → neuronal GLP-2 release → Glp2r activation in the hypothalamus and brain stem → autonomic control of peripheral glucose metabolism. Regardless of GLP-2 secreted from L cells in the gut or released from PPG neurons in the brain stem, Glp2r activation on DMV neurons in the brain stem may modulate vagal outflow, reprogramming peripheral glucose metabolism.

How does GLP-2 act in brain stem DMV neurons? Studies show that the plasticity at the NTS-DMV synapse depends on cAMP-PKA pathway (15). Little is known about Glp2r-activated intracellular signaling pathways in the brain stem, yet the fourth intracerebroventricular GLP-2 suppresses food intake (46), and GLP-2 directly excites liver-projecting DMV neurons (unpublished data). GLP-2 activates cAMP-PKA signaling pathway (16, 81, 128, 137). As GLP-2 regulates mRNA expression of hypothalamic genes in a PKA-dependent manner (28), GLP-2 potentiates L-type Ca\(^{2+}\) channel activity in hippocampal neurons (131). Brain stem Glp1r activation suppresses food intake and body weight through PKA-mediated suppression of AMPK and activation of MAPK (48, 49). We speculate that GLP-2R activation → DMV neuronal excitation (via PKA-dependent long-term potentiation) → ACh release (as a rapid-acting neurotransmitter) on postganglionic neurons → glycemic control. Thus, we favor a model that the DMV Glp2r activation initiates the PKA-dependent Ca\(^{2+}\)-triggered depolarization, enhancing the synaptic transmission in the DMV → glycemic control. However, this model for Glp2r action in the brain stem waits for experimental support.

Do GLP-2-sensitive ARC POMC neurons signal to brain stem DVC via α-MSH-Mc4r pathway? ARC POMC neurons project to selected target sites in the hypothalamus and brain stem (35, 63). A brain stem DVC (including NTS and DMV) integrates hypothalamic inputs and vagal afferent inputs to regulate the autonomic control of feeding behavior and glucose homeostasis (71, 87, 116, 139, 140). As suggested, ARC DVC-projecting POMC neurons may represent an anatomically and functionally distinct subgroup of POMC neurons (63, 140). As the major α-MSH receptor, Mc4r plays a pivotal role in energy homeostasis and is a key target for the treatment of obesity and diabetes (143). Mc4r is heavily expressed in the brain stem DVC (42, 64, 90). The brain stem DVC is a critical site for ARC POMC-derived α-MSH input to suppress food intake and HGP (10, 25, 36, 44, 79, 110), yet little is known about how the NTS-DMV plasticity is modulated to fine-tune hepatic vagal output, influencing HGP (125). Interestingly, local infusion of GLP-2 (2.5 nmol into the 4th ventricle) suppresses food intake and gastric emptying, but these effects are abolished in Mc4r KO mice (46). Activation of Mc4r-positive cholinergic neurons in the DMV would enhance excitatory input to the liver, suppressing HPG (42, 110). Thus, it is conceivable that GLP-2 activates POMC neurons to release α-MSH, activating Mc4r-positive neurons (expressing choline acetyltransferase) in the DMV that enhances hepatic vagal output to suppress HGP.

Does GLP-2 directly modulate vagal afferents to improve glycemic control? Vagal afferent neurons convey primarily information from the viscera to the CNS. Vagal afferents may be a key neural pathway that regulates food intake, gastrointestinal motility, and glucose homeostasis (23, 42, 42, 130). Activation of N-methyl-D-aspartate receptors in the DVC is sufficient to trigger a brain-liver axis to lower HGP (71, 72, 105). Moreover, gastrointestinal hormones excite neurons in the rodent nodose ganglia by closure of K\(^{+}\) channels (40, 51). GLP-2 activates vagal afferent pathway where Glp2r is expressed (95). Interestingly, GLP-2 mediates the gut-brain communication via activating vagal afferents (94, 95). We speculate that Glp2r activation on vagal afferents may influence neural inputs to 1) preproglucagonergic (PPG) neurons in the brain stem NTS → GLP-2 release → Glp2r activation in the hypothalamic ARC/DMH and the brain stem DMV → autonomic outputs; and 2) POMC neurons in the brain stem NTS → α-MSH release → Mc4r activation in the hypothalamic ARC/DMH and the brain stem DMV → autonomic outputs. However, GLP-2-modulated neural circuitries (including distinct neurons on vagal afferents) have not been identifi-
fied. Of note, chemical and/or surgical vagotomy does not selectively inactivate distinct types of neurons (12). It will be important to reassess the physiological relevance of targeted neurons in the vagus using the Cre-dependent pharmacogenetic modulation and determine whether GLP-2-induced activation of vagal afferent neurons impacts glucose homeostasis and insulin sensitivity.

Does augmented GLP-2 signaling contribute to improving metabolic outcomes after bariatric surgery? Bariatric surgery (particularly RYGB) is the most effective therapy for morbid obesity and diabetes (19, 26, 111), in which the gut-brain axis is highly involved in mediating beneficial effects on food intake and glycemic control. A recent report indicates that metabolic reprogramming of glucose to support intestinal hypertrophy renders the gut itself a major tissue for glucose disposal, contributing to improved metabolic outcomes after RYGB (113). In fact, RYGB increases blood GLP-2 (by 200%) at postprandial status (73) and enhances proliferation rates of the intestinal crypt epithelial cells, suggesting that GLP-2 (as a potent enterotrophic factor) may be an important signal to drive intestinal adaptation. However, it is still unclear whether GLP-2 is a key neuroendocrine signal via the gut-brain axis to enhance insulin sensitivity and glucose homeostasis following RYGB.

Limitations are not addressed in current GLP-2 studies. There are two major limitations in current studies. One is how to define the physiological significance of Glp2r in site-specific populations of POMC neurons. The POMC-Cre-mediated recombination of floxed Glp2r allele will result in Glp2r deletion in POMC neurons, including POMC neurons in the hypothalamus, brain stem, and pituitary gland. Thus, Glp2r metabolic action in extrahypothalamic POMC neurons should be considered as well. However, the metabolic phenotype of POMC-Glp2r knockout mice may be largely attributed to the Glp2r deletion in POMC neurons in the hypothalamic ARC (118). There are three lines of evidence to support this speculation: 1) The POMC Cre mouse line had little Cre expression in the brain stem NTS when crossed with a Cre reporter mouse line (such as Rosa26-tdTomatto). 2) The Glp2r has not been shown to express in the brain stem NTS or pituitary gland. 3) POMC neurons in the ARC play important roles in energy/glucose homeostasis (101). To further dissect the physiological role of Glp2r in site-specific populations of POMC neurons, one should manipulate Glp2r deficiency in distinct sites by nucleus-specific injection of Cre-dependent, lentiviral mediated Glp2r shRNA (to knock down Glp2r expression).

Another one is how to distinguish the physiological significance of GLP-2 from distinct sources in the control of energy and glucose homeostasis. GLP-2 can be originated from endocrine L cells in the gut and PPG neurons in the brain stem NTS, while Glp2r is expressed in endocrine and neural cells. Thus, GLP-2 action can be mediated via endocrine and neural manners. In a majority of pharmacological studies, administration routes are used to distinguish so-called peripheral vs. central action of neuropeptides. This is not appropriate specifically for neuropeptides that cross the blood-brain barrier via passive permeability or active transport. We speculate that peripheral GLP-2 can be transported into the hypothalamic ARC, where the blood-brain barrier is semipermeable or taken up through the median eminence. In addition, it is very challenging to quantify metabolic effects of endocrine or neural GLP-2 (i.e., originated from endocrine L cells or PPG neurons). As a fact, there are no genetic approaches available to distinguish the physiological significance of GLP-2 from distinct sources. Instead, we propose to define the functional relevance of CNS GLP-2 by deleting its receptor only in central distinct neurons. It is demonstrated using tissue-specific Glp2r KO mouse model that Glp2r activation in POMC neurons is required for intravenous and intracerebroventricular GLP-2 to promote glucose homeostasis and insulin sensitivity, and for GLP-2 to modulate the excitability of hypothalamic POMC neurons ex vivo (118),
pointing to the functional relevance of Glp2r action on POMC neurons regardless of the source of GLP-2.

Innovative Approaches Need To Define the CNS Control of Feeding and Metabolism

One major interest is to determine the CNS control of glucose homeostasis and feeding behavior. Increasing evidence indicates that the CNS neural circuitry is selective for glucose homeostasis or feeding behavior, in which subgroups of distinct neurons are segregated. To remotely modulate activation or inactivation of targeted neurons in conscious mice, one innovative pharmacogenetic approach, namely designer receptors exclusively activated by designer drugs (DREADDs), has been employed to elucidate the CNS neural circuits for feeding behavior (69). It has been very challenging to genetically dissect metabolic actions of targeted neurons on glycemic control or insulin sensitivity, which are confounded per se by developmental, behavioral, or body-adiposity factors. The DREADDs can remotely, acutely, and reversibly control circuit activity in vivo and, thus, will provide a powerful approach to dissect metabolic phenotypes of targeted neurons in defined spatial and temporal manners. Another state-of-the-art approach is in vivo stable isotopic tracer methodologies (in conjunction with oral glucose tolerance test and hyperinsulineemic euglycemic clamp) to quantify dynamic glycemic kinetics at postprandial and postabsorptive states and assess tissue-specific insulin sensitivity in conscious mice (46). Thus, it will be instrumental to combine in vivo stable isotopic tracer methodologies (including MS-based targeted metabolomics) with the remote control of targeted neuron approaches (such as DREADDs) to address the CNS control of glucose metabolism independent of body adiposity.

Another major interest is to map distinct hypothalamic-brain stem neural circuits underlying glycemic control. Optogenetic activation and inactivation of targeted neural circuitry have been used to establish how the neural circuits are wired functionally in the brain in vivo. Specifically, optogenetics has been successfully employed to define the hypothalamic neural circuitry controlling feeding behavior in rodents (20). Future studies are warranted to integrate optogenetic, electrophysiological, and metabolic approaches to define the functioning neural circuits responsible for glucose homeostasis.

Perspectives and Significance

GLP-1 and -2 are coproduced from enteroendocrine L cells in the gut and preproglucagonergic neurons in the brain stem. Dietary macronutrients and gut microbiota-derived metabolites (secondary bile acids and short-chain fatty acids) function as effective secretagogues of GLP-1 and-2. Because of Glp2r (secondary bile acids and short-chain fatty acids) function as effective secretagogues of GLP-1 and-2. Because of Glp2r expression in nutrient-sensing endocrine cells and neurons, GLP-2 acts as a key endocrine and neural signal to regulate energy balance and glucose homeostasis. In the gastrointestinal tract, GLP-2 promotes intestinal epithelial homeostasis and function, enhances intestinal nutrient absorption and blood flow, and inhibits gastrointestinal motility, thus controlling energy intake in the first place. In the hypothalamus and brain stem, Glp2r plays physiological roles in regulating food intake and glucose homeostasis, which are mediated through fine-tuning vagal outputs via the proposed neural circuits (Fig. 2). New evidence underscores the CNS GLP-2-mediated promotion of glycemic control and insulin sensitivity via the PI3K-dependent, central melanocortin system. Importantly, the GLP-2 gut-brain axis may be physiologically modulated by nutrition, gut microbiota, and bariatric surgery. Using Glp2r-floxed mouse line in combination of state-of-the-art approaches (such as stable isotopic tracer methodologies and the remote control of targeted neurons), one will further dissect the GLP-2 gut-brain axis and identify novel targets for the treatment of gastrointestinal diseases, obesity, and diabetes.

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DISCLOSURES

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Author contributions: X.G. conception and design of research; X.G. performed experiments; X.G. analyzed data; X.G. interpreted results of experiments; X.G. prepared figures; X.G. drafted manuscript; X.G. edited and revised manuscript; X.G. approved final version of manuscript.

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