Glucose-dependent insulinogetic polypeptide (GIP) promotes glucose-dependent insulin secretion. However, GIP also enhances glucocorticoid secretion and promotes adiposity. Because obesity and diabetes are glucocorticoid dependent, we examined whether the effects of GIP on energy balance and glycemia are regulated by glucocorticoids using pharmacological activation of GIP receptor (GIPR) signaling with [D-Ala²]GIP in mice and in Y1 adrenergic cells. Genetic elimination of GIPR activity was also studied in normal- and high fat (HF)-fed Gipr⁻/⁻ mice. [D-Ala²]GIP increased murine corticosterone levels in a GIPR-dependent manner. Conversely, basal corticosterone levels were reduced, whereas food deprivation resulted in significantly enhanced plasma corticosterone levels in Gipr⁻/⁻ mice. [D-Ala²]GIP increased cAMP levels, activated ERK1/2, increased expression of steroidogenic genes, and increased neutral lipid storage in Y1GIPR cells. Gipr⁻/⁻ adrenal glands demonstrated a twofold upregulation of the ACTH receptor mRNA and increased sensitivity to ACTH ex vovo. Although HF-fed Gipr⁻/⁻ mice exhibited significantly lower plasma corticosterone, glucocorticoid-treated HF-fed Gipr⁻/⁻ mice had similar energy balance and glycemia compared with Gipr⁺/⁺ controls. Hence, although the Gipr is essential for adrenal steroidogenesis and links HF feeding to increased levels of corticosterone, reduced glucocorticoid levels do not significantly contribute to the enhanced metabolic phenotypes in HF-fed Gipr⁻/⁻ mice.

Glpse-dependent insulinogetic polypeptide (GIP) is a 42-amino acid peptide hormone released from intestinal K cells upon nutrient ingestion (1). The original description of GIP bioactivity encompassing inhibition of gastric emptying was subsequently expanded to include potentiation of glucose-dependent insulin secretion. GIP also can stimulate lipogenesis (2,3) and increase the activity of lipoprotein lipase in adipocytes in part through stimulatory effects on resistin secretion (4,5), thus enhancing fatty acid incorporation into adipose tissue.

Complementary insights into the physiological importance of endogenous GIP action have been obtained from studies using antagonists, elimination of GIP-producing K cells, or receptor knockout mice. Reduction or elimination of GIP action promotes resistance to genetic and high fat (HF) diet–induced obesity, increased energy expenditure and activity, reduced fat deposition in nonadipose and adipose depots, improved insulin sensitivity, and lower plasma resistin levels (5–9). Therefore, it remains unclear whether enhancement or reduction of GIP action is the preferred therapeutic strategy for the treatment of obesity-associated type 2 diabetes.

An additional extrapancreatic locus of GIP action is the adrenal cortex. Expression of the GIP receptor (GIPR) has been demonstrated in the adrenal cortex by radioligand binding (10) and RT-PCR (11) in rodents; however, the GIPR is not expressed in normal human adrenal glands (12). Ectopic expression of the GIPR in the human adrenal gland causes significant hypercortisolemia after meal ingestion and leads to Cushings syndrome (13), demonstrating that human GIPR activation is capable of robustly activating adrenal glucocorticoid secretion. Indeed, GIP administration increases corticosterone levels in rats (10), and isolated rat adrenocortical zona fasciculata/reticularis cells respond to GIP in a cAMP-dependent protein kinase manner (10). However, the mechanisms through which GIP stimulates glucocorticoid secretion and the physiological importance of adrenal GIP action remains poorly understood.

Chronic elevations of glucocorticoid levels promote obesity and/or metabolic syndrome, and many rodent models of obesity or insulin resistance, including ob/ob and db/db mice, Zucker and ZDF rats, HF-fed rodents, and streptozotocin-induced diabetic rodents, exhibit elevations in glucocorticoids (14–17). Furthermore, adrenalectomy or glucocorticoid receptor (GR) antagonists ameliorate or in some cases prevent diabetes and obesity phenotypes (18,19). Accordingly, we hypothesized that antagonism or removal of the GIPR-dependent stimulation of corticosterone secretion after nutrient ingestion may contribute to one or more of the phenotypes exhibited by Gipr⁻/⁻ mice. We now show that activation or disruption of the GIPR modulates glucocorticoid levels in mice, and GIP directly enhances glucocorticoid synthesis and secretion in adrenocortical cells. However, the reduction in glucocorticoid levels observed in Gipr⁻/⁻ mice does not substantially contribute to the phenotypes of improved glucose tolerance and resistance to diet-induced obesity in HF-fed Gipr⁻/⁻ mice.

**RESEARCH DESIGN AND METHODS**

All experiments were done using male mice acclimatized to handling before commencement of experiments. Wild-type C57BL/6 mice were obtained from the Toronto Centre for Phenogenomics (TCP, Toronto, ON, Canada). The generation and characterization of Gipr⁻/⁻ mice has been described previously (20). Mice were housed under a 12-h light/dark cycle in the TCP animal.
GIP CONTROLS ADRENAL STEROIDOGENESIS

**RESULTS**

The GIPR agonist [D-Ala²]GIP increases plasma corticosterone in mice via the GIPR. [D-Ala²]GIP administration to overnight fasted C57BL/6 mice induced a brisk rise in corticosterone levels (Fig. 1A); in contrast, no increase in plasma corticosterone levels occurred after [D-Ala²]GIP administration in Gipr⁻/⁻ mice (Fig. 1B). To determine if chronic GIPR activation alters corticosterone levels, we assessed diabetic mice treated with saline or [D-Ala²]GIP twice daily for 60 days (26). Corticosterone levels were more than threefold higher in mice chronically injected with [D-Ala²]GIP (Fig. 1C).

Basal corticosterone levels are reduced in Gipr⁻/⁻ mice. We next assessed plasma corticosterone in Gipr⁻/⁻ mice. Corticosterone levels were reduced in Gipr⁻/⁻ mice (Fig. 1D) during the peak of the circadian corticosterone rhythm at 1800 h, 1 h prior to their dark cycle. The lower corticosterone levels in Gipr⁻/⁻ mice were not associated with simultaneous differences in glycemia (data not shown). We next examined the corticosterone response to stress in Gipr⁻/⁻ mice. Plasma corticosterone responses to restraint stress or insulin-induced hypoglycemia were comparable across genotypes (Fig. 2). In a similar manner, exogenous administration of ACTH produced robust yet comparable increases in plasma corticosterone in Gipr⁻/⁻ versus Gipr⁺/⁺ mice (Fig. 2). In contrast, corticosterone levels were more than threefold higher in Gipr⁻/⁻ mice after 24 h of food deprivation (Fig. 2). Glucose levels were
not different between \( \text{Gipr}^{+/+} \) versus \( \text{Gipr}^{-/-} \) mice during these experiments (data not shown). Corticosterone levels are reduced in HF-fed \( \text{Gipr}^{-/-} \) mice in the absence of reduced hypothalamic–pituitary axis activation. HF feeding increases basal corticosterone levels (17). Accordingly, we examined whether the \( \text{Gipr} \) links excess nutrients to increased plasma corticosterone. Remarkably, basal corticosterone levels were reduced by 50% in \( \text{Gipr}^{-/-} \) mice after 2 weeks of HF feeding (Fig. 3A). However, levels of plasma ACTH (Fig. 3A), pituitary proopiomelanocortin (\( \text{pomc} \)) (Fig. 3B), and hypothalamic corticotrophin-releasing hormone (\( \text{crh} \)) mRNA transcripts (Fig. 3C) were comparable in \( \text{Gipr}^{+/+} \) versus \( \text{Gipr}^{-/-} \) mice. GR expression also was similar in the pituitary, hypothalamus, and epididymal white adipose tissue of \( \text{Gipr}^{+/+} \) versus \( \text{Gipr}^{-/-} \) mice (Fig. 3B–D), and expression of the glucocorticoid synthesizing enzyme 11\( \beta \)-hydroxysteroid dehydrogenase 1 (11\( \beta \)-HSD1) was similar between genotypes (Fig. 3D). Hence, elimination of the \( \text{Gipr} \) is not associated with generalized perturbations in key molecular components of the hypothalamic–pituitary axis (HPA) despite expression of \( \text{Gipr} \) mRNA at all levels of the HPA axis (Supplementary Fig. 1), nor is it associated with alterations in several genes regulating glucocorticoid synthesis and action in key target tissues. \( \text{Gipr}^{-/-} \) mice exhibit altered adrenal expression of steroidogenic genes and increased sensitivity to ACTH. To delineate mechanism(s) through which GIPR signaling controls corticosterone in mice, we assessed the expression of genes regulating adrenal steroidogenesis in \( \text{Gipr}^{+/+} \) mice (n = 8–12). D: Basal, unstressed corticosterone levels are reduced in \( \text{Gipr}^{-/-} \) mice compared with wild-type littermates (n = 7–10). * \( P < 0.05 \), ** \( P < 0.01 \) [D-Ala\(^2\)]GIP vs. saline-injected control or \( \text{Gipr}^{-/-} \) vs. \( \text{Gipr}^{+/+} \).
GIP CONTROLS ADRENAL STEROIDOGENESIS

versus Gipr<sup>−/−</sup> mice after 2 weeks of HF feeding. Levels of StAR, cyp11A1, and dax1 mRNA transcripts were comparable in Gipr<sup>−/−</sup> mice, sf1 mRNA transcripts were significantly reduced (P < 0.05), creb1 mRNA transcripts were increased (P = 0.07), and mc2r mRNA transcripts were significantly higher (P < 0.01) in Gipr<sup>−/−</sup> adrenals (Fig. 4A).

To assess whether increased levels of mRNA transcripts for the ACTH receptor (mc2r) reflected functionally increased sensitivity to ACTH, we administered a low dose of ACTH (1 nmol/L) to Gipr<sup>−/−</sup> and Gipr<sup>+/+</sup> mouse adrenals ex vivo. A significantly greater corticosterone response to ACTH was detected from Gipr<sup>−/−</sup> mouse adrenals, consistent with enhanced ACTH sensitivity (Fig. 4B).

GIP regulates lipid accumulation in adrenocortical cells. Because GIP enhances adrenal corticosterone secretion, we hypothesized that the Gipr regulates expression of genes controlling adrenal cholesterol homeostasis. Although the majority of mRNA transcripts encoding genes within the cholesterol biosynthetic and transport pathways were not differentially expressed in Gipr<sup>−/−</sup> versus Gipr<sup>+/+</sup> adrenal glands (Fig. 5A), expression of sf-1b was significantly reduced in Gipr<sup>−/−</sup> adrenal glands (Fig. 5A). Since SR-B1 is responsible for selective uptake of cholesterol esters from HDL, the primary source of adrenal cholesterol stores in mice (27,28), we examined levels of neutral lipids in adrenal glands of Gipr<sup>−/−</sup> mice using Oil Red O histochemistry. The intensity of Oil Red O staining in the adrenal cortex was clearly reduced after 9 weeks of a HF diet in Gipr<sup>−/−</sup> mice (Fig. 5B). Conversely, activation of the GIPR with [D-Ala<sup>2</sup>]GIP significantly increased incorporation of Oil Red O in Y1GIPR cells (Fig. 5C).

[D-Ala<sup>2</sup>]GIP directly stimulates steroidogenesis and increases expression of steroidalogenic genes in Y1 cells. As native Y1 adrenocortical cells do not express an endogenous GIPR (Supplementary Fig. 1), we used Y1 mouse adrenocortical cells stably transfected with the rat GIPR cDNA. Y1GIPR cells exhibited a robust dose-dependent increase in cAMP levels in response to GIP (Fig. 6A).

In a similar manner, ERK1/2 phosphorylation was rapidly increased after exposure to [D-Ala<sup>2</sup>]GIP (P < 0.05) (Fig. 6B). Therefore, we assessed progesterone secretion in response to [D-Ala<sup>2</sup>]GIP. A fivefold increase in progesterone secretion was observed after treatment with [D-Ala<sup>2</sup>]GIP (P < 0.001) (Fig. 6C).}

Corticosterone supplementation does not exacerbate body weight gain in Gipr<sup>−/−</sup> mice. To determine if lower corticosterone levels in Gipr<sup>−/−</sup> mice contribute to their

FIG. 3. Corticosterone levels are reduced in HF-fed Gipr<sup>−/−</sup> mice. Gipr<sup>+/+</sup> and Gipr<sup>−/−</sup> mice were fed a 45% HF diet for 2–3 weeks and basal, unstressed HPA parameters measured by real-time qRT-PCR. A: Plasma corticosterone levels were reduced in Gipr<sup>−/−</sup> mice without changes in plasma ACTH levels. Gene expression of pome in the pituitary gland (B) and creb in the hypothalamus (C) were not altered in Gipr<sup>−/−</sup> mice. In a similar manner, Gr expression was not changed in the pituitary (B), hypothalamus (C), or epididymal white adipose tissue (D) of Gipr<sup>−/−</sup> mice. Gene expression of the glucocorticoid synthesizing enzyme 11β-HSD1 (D) was not changed in Gipr<sup>−/−</sup> mice. *P < 0.05 vs. Gipr<sup>+/+</sup> mice (n = 4–11 per group).

FIG. 4. Altered expression of steroidalogenic genes and increased sensitivity to ACTH in adrenal glands of Gipr<sup>−/−</sup> mice. A: Expression of genes involved in adrenal steroidogenesis were measured by real-time qRT-PCR in adrenal glands from Gipr<sup>+/+</sup> and Gipr<sup>−/−</sup> mice after 2 weeks of HF feeding (n = 8–9 per group). B: Ex vivo adrenal sensitivity to ACTH (1 nmol/L) was measured in adrenal glands from Gipr<sup>+/+</sup> and Gipr<sup>−/−</sup> mice after 5 weeks HF feeding (n = 5 per group). *P < 0.05, **P < 0.01 vs. Gipr<sup>+/+</sup> mice.
metabolic phenotype, Gip^{+/+} and Gip^{-/-} mice were supplemented with 5 μg/mL corticosterone in their drinking water and fed a HF diet for 22 weeks. Water and corticosterone intake were not affected by genotype (data not shown). Adrenal weights after 22 weeks were not different between vehicle-treated Gip^{+/+} and Gip^{-/-} mice. However, adrenal weights (Fig. 7A) were significantly reduced in both genotypes as a result of corticosterone supplementation (P < 0.05), consistent with feedback inhibition of the HPA axis from exogenous corticosterone administration. Body weights increased over time with HF feeding (Fig. 7B), and Gip^{-/-} mice gained less weight than wild-type littermates. However, weight gain was not affected by corticosterone supplementation in Gip^{+/+} versus Gip^{-/-} mice. Nocturnal food intake was slightly reduced in Gip^{-/-} mice (P < 0.02), as was ad libitum food intake (P = 0.02) (Supplementary Fig. 2), although this was no longer significant when normalized to body weight. Food intake was not altered by corticosterone supplementation. Locomotor activity was increased in Gip^{-/-} mice during the dark phase compared with Gip^{+/+} mice; however, neither VO_{2} nor locomotor activity was affected by corticosterone supplementation (Fig. 7C and D). Gip^{-/-} mice had reduced fat mass; however, corticosterone supplementation had no effect on fat (Fig. 7E) or lean mass (data not shown) in Gip^{-/-} mice.

**Corticosterone supplementation does not impair glucose homeostasis in Gip^{-/-} mice.** Overnight fasting glucose levels (~16-h fast) were not different between genotypes or affected by corticosterone supplementation (Fig. 8A and B). Corticosterone supplementation had no effect on oral or intraperitoneal glucose tolerance in Gip^{+/+} or Gip^{-/-} mice (Fig. 8A and B). Despite comparable glucose levels, insulin levels (Fig. 8A and B) and insulin-to-glucose ratios (P < 0.05) (data not shown) to oral but not intraperitoneal glucose were reduced in Gip^{-/-} mice. Insulin sensitivity assessed by ITT was neither different between genotypes nor affected by corticosterone supplementation (Fig. 8C).

**DISCUSSION**

We have shown that activation of the GIPR increases plasma glucocorticoid levels in mice and that GIP directly activates steroidogenic gene expression in mouse adrenocortical cells. It seems likely that GIP also promotes steroidogenesis via increasing uptake of cholesterol since Gip^{-/-} mice exhibited a twofold reduction of neutral lipid staining, whereas Y1GIPR cells stimulated with [D-Ala^{2}]GIP expressed higher transcript levels of sr-b1 mRNA transcripts and had reduced neutral lipid accumulation in adrenal glands from Gip^{+/+} and Gip^{-/-} mice by real-time qRT-PCR after 2 weeks HF feeding (n = 8–9 per group). B: The intensity of Oil Red O staining for neutral lipids is reduced in adrenal glands from Gip^{-/-} mice compared with Gip^{+/+} littermates after 9 weeks of HF feeding (n = 3 per group; original magnification x10). C: Cortex; M, medulla. C: Elution of Oil Red O from Y1GIPR adrenocortical cells is increased after 7 days treatment with [D-Ala^{2}]GIP (n = 3 per group). *P < 0.05 vs. Gip^{+/+} mice, **P < 0.01 vs. saline control. (A high-quality digital representation of this figure is available in the online issue.)
Nevertheless, the increased adrenal expression of the ACTH receptor and enhanced adrenal sensitivity to ACTH in adrenal glands from \( Gipr^{−/−} \) mice suggest the evolution of adaptive compensatory mechanisms that mask the impact of loss of adrenal GIP action. Enhanced ACTH sensitivity in \( Gipr^{−/−} \) mice likely diminishes the extent of corticosterone deficiency and metabolic effects that might otherwise arise pursuant to elimination of GIPR action in the adrenal gland.

Further evidence for a direct effect of GIP on the adrenal gland was obtained in experiments using Y1GIPR cells. [D-Ala\(^2\)]GIP directly stimulated steroidogenesis, increased cAMP, activated the ERK pathway, and increased \( \text{StAR} \), \( \text{cyp11a1} \), and \( \text{sr-b1} \) gene expression. Conversely, mRNA levels of \( \text{sf-1} \), a transcription factor critical for regulation of adrenal steroidogenesis (31), and levels of \( \text{sr-b1} \), a downstream target of SF-1 (32), were reduced in adrenal glands from \( Gipr^{−/−} \) mice. GIP likely mediates some of its effects on the adrenal gland via modifying cholesterol uptake and/or storage. \( Gipr^{−/−} \) mice had less neutral lipid staining in the adrenal cortex after 9 weeks of HF feeding, whereas [D-Ala\(^2\)]GIP increased neutral lipid accumulation in Y1GIPR cells. Since \( \text{sr-b1} \) mediates selective uptake of cholesterol from HDL, the most important pathway for adrenal cholesterol uptake in mice, and depletion of \( \text{sr-b1} \) leads to deficits in corticosterone (28,33), it is likely that GIP mediates adrenal steroidogenesis in part via this cholesterol uptake pathway.

Although the corticosterone responses to restraint stress, insulin-induced hypoglycemia, and high-dose ACTH were normal in \( Gipr^{−/−} \) mice, the more chronic stressor of 24-h food deprivation elicited a threefold greater corticosterone response in \( Gipr^{−/−} \) mice. In contrast to potent stressors such as restraint and insulin, food deprivation does not significantly increase ACTH levels, but it does increase basal corticosterone levels by reducing hepatic glucocorticoid clearance (34,35). Hence, at the low ACTH levels associated with food deprivation, the greater adrenal sensitivity to ACTH in \( Gipr^{−/−} \) mice may be unmasked, leading to differentially greater increases in corticosterone responses in \( Gipr^{−/−} \) mice. In contrast, no differences in corticosterone levels are apparent under situations where ACTH levels would already be expected to be high, as exemplified by restraint and insulin. Thus, it is likely that food deprivation is associated with reduced hepatic clearance of corticosterone and enhanced sensitivity to

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**FIG. 6.** [D-Ala\(^2\)]GIP stimulates steroidogenesis in Y1 cells. **A**: GIP stimulates an increase in cAMP production by Y1 mouse adrenocortical cells stably transfected with the GIPR in a dose-dependent manner. **B**: Incubation of 72-h serum-starved Y1GIPR cells with 100 nmol/L [D-Ala\(^2\)]GIP increases ERK1/2 phosphorylation (P-ERK1/2; \( n = 6 \) per group). S, saline; G, [D-Ala\(^2\)]GIP; A, ACTH. **C**: Treatment (24 h) of Y1 cells with [D-Ala\(^2\)]GIP stimulates progesterone production. **D**: Incubation (6 h) of Y1 adrenocortical cells with [D-Ala\(^2\)]GIP increases \( \text{StAR} \), \( \text{cyp11a1} \), and \( \text{sr-b1} \) mRNA transcripts measured by real-time qRT-PCR \( ( n = 5–7 \) per group). \( **P < 0.01 \) vs. saline, ***\( P < 0.001 \) vs. empty vector/saline.
lower levels of ACTH, leading to hypercorticosteronemia in Gipr<sup>2/2</sup> mice.

Glucocorticoids regulate metabolism through stimulation of hepatic glucose production (36), impairment of insulin sensitivity and glucose tolerance (37), inhibition of insulin secretion (38), and facilitation of lipolysis (23). Chronic elevations of glucocorticoids promote fat deposition (23,39), insulin resistance (39), hepatosteatosis, hyperphagia, and decreased locomotion (39). Many commonly used rodent models of obesity or insulin resistance, including ob/ob and db/db mice, Zucker and ZDF rats, HF-fed rodents, and streptozotocin-induced diabetic rodents, exhibit elevations in glucocorticoids (14–17). Adrenalectomy or administration of a glucocorticoid antagonist can ameliorate or in some cases reverse the abnormal metabolic phenotype (18,19), illustrating the importance of glucocorticoids in the development of rodent obesity and diabetes. Administration of a peptide GIPR antagonist in HF-fed mice lowers corticosterone levels in association with reduced body weight and fat deposition, increased locomotion, and improved glucose homeostasis (7,8,40). However, our current data in HF-fed Gipr<sup>2/2</sup> mice suggest that modest reductions in plasma corticosterone do not appear to substantially...
modify the dominant metabolic phenotypes arising after HF feeding in Gipr<sup>−/−</sup> mice.

Corticosterone supplementation did not significantly modify food intake, energy expenditure, weight gain, or fat mass in Gipr<sup>+/+</sup> and Gipr<sup>−/−</sup> mice. However, corticosterone supplementation slightly improved oral but not intraperitoneal glucose tolerance in wild-type mice. This modest improvement was likely related to the small reductions in body weight and fat mass induced by corticosterone supplementation that would in turn improve glucose disposal. This reduction in fat mass may be related to the lipolytic effects of corticosterone at low concentrations (23). It is likely that the upregulation of ACTH sensitivity in Gipr<sup>−/−</sup> mice resulted in only a subtle reduction in plasma corticosterone that was not sufficient to lower weight gain or modify energy balance and glucose homeostasis. Consistent with our current data, Irwin et al. (7) demonstrated that administration of the GIP antagonist Pro(3)GIP to ob/ob mice for 60 days significantly improved glucose control and insulin sensitivity, without concomitant changes in circulating corticosterone.

In summary, we show that GIP stimulates plasma glucocorticoid levels in mice and demonstrate that GIP directly activates steroidogenesis through stimulation of steroidogenic genes as well as sv-b1 expression and consequent adrenocortical lipid deposition. Gipr<sup>−/−</sup> mice compensate for disruption of GIP action in the adrenal gland via upregulation of mcv2 expression and enhanced ACTH sensitivity. Corticosterone supplementation did not reverse the beneficial metabolic phenotype of HF-fed Gipr<sup>−/−</sup> mice, including resistance to diet-induced obesity and maintenance of oral glucose tolerance with lower levels of plasma insulin, implicating organs such as the brain and adipose tissue as potential mediators of the favorable Gipr<sup>−/−</sup> phenotype. Our findings may have relevance for envisioned therapeutic strategies using GIPR antagonists for the treatment of obesity and diabetes in human subjects. Because the GIP–adrenal axis does not appear to be functional in normal human subjects, the observation that manipulation of corticosterone levels does not substantially abrogate the beneficial metabolic phenotype of Gipr<sup>−/−</sup> mice has positive implications for targeting the GIPR in human subjects.

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Supplementary Figure 1. Representative blots demonstrating expression of \textit{Gipr} mRNA in the pituitary, hypothalamus and adrenal gland in \textit{Gipr}+/+ but not \textit{Gipr}−/− mice.
Supplementary Figure 2. Nocturnal food intake was slightly reduced in Gipr-/- mice (P<0.02) as was ad libitum food intake (P=0.02), although this was no longer significant when normalized to body weight. Food intake was not altered by corticosterone supplementation (Cort).