An increase in hepatic glucose production (HGP) is a key feature of type 2 diabetes. Excessive signaling through hepatic G\textsubscript{s}-linked glucagon receptors critically contributes to pathologically elevated HGP. Here, we tested the hypothesis that this metabolic impairment can be counteracted by enhancing hepatic G\textsubscript{i} signaling. Specifically, we used a chemogenetic approach to selectively activate G\textsubscript{i}-type G proteins in mouse hepatocytes in vivo. Unexpectedly, activation of hepatic G\textsubscript{i} signaling triggered a pronounced increase in HGP and severely impaired glucose homeostasis. Moreover, increased G\textsubscript{i} signaling stimulated glucose release in human hepatocytes. A lack of functional G\textsubscript{i}-type G proteins in hepatocytes reduced blood glucose levels and protected mice against the metabolic deficits caused by the consumption of a high-fat diet. Additionally, we delineated a signaling cascade that links hepatic G\textsubscript{i} signaling to ROS production, JNK activation, and a subsequent increase in HGP. Taken together, our data support the concept that drugs able to block hepatic G\textsubscript{i}-coupled GPCRs may prove beneficial as antidiabetic drugs.
Hepatic $G_i$ signaling regulates whole-body glucose homeostasis

Mario Rossi,1 Lu Zhu,1 Sara M. McMillin,1 Sai Prasad Pydi,1 Shanu Jain,1 Lei Wang,1 Yinghong Cui,1 Regina J. Lee,1 Amanda H. Cohen,1 Hideaki Kaneto,2 Morris J. Birnbaum,3 Yanling Ma,4 Yaron Rotman,4 Jie Liu,5 Travis J. Cyphert,6 Toren Finkel,5 Owen P. McGuinness,6 and Jürgen Wess1

1Molecular Signaling Section, Laboratory of Bioorganic Chemistry, National Institute of Diabetes and Digestive and Kidney Diseases (NIDDK), Bethesda, Maryland, USA. 2Osaka University Graduate School of Medicine, Osaka, Japan. 3Cardiovascular and Metabolic Diseases (CVMED), Pfizer Inc., Cambridge, Massachusetts, USA. 4Liver and Energy Metabolism Unit, Liver Diseases Branch, NIDDK, Bethesda, Maryland, USA. 5Center for Molecular Medicine, National Heart, Lung, and Blood Institute (NHLBI), Bethesda, Maryland, USA. 6Departments of Molecular Physiology and Biophysics, Vanderbilt University Medical Center, Nashville, Tennessee, USA.

An increase in hepatic glucose production (HGP) is a key feature of type 2 diabetes. Excessive signaling through hepatic $G_i$–linked glucagon receptors critically contributes to pathologically elevated HGP. Here, we tested the hypothesis that this metabolic impairment can be counteracted by enhancing hepatic $G_i$ signaling. Specifically, we used a chemogenetic approach to selectively activate $G_i$-type G proteins in mouse hepatocytes in vivo. Unexpectedly, activation of hepatic $G_i$ signaling triggered a pronounced increase in HGP and severely impaired glucose homeostasis. Moreover, increased $G_i$ signaling stimulated glucose release in human hepatocytes. A lack of functional $G_i$-type G proteins in hepatocytes reduced blood glucose levels and protected mice against the metabolic deficits caused by the consumption of a high-fat diet. Additionally, we delineated a signaling cascade that links hepatic $G_i$ signaling to ROS production, JNK activation, and a subsequent increase in HGP. Taken together, our data support the concept that drugs able to block hepatic $G_i$–coupled GPCRs may prove beneficial as antidiabetic drugs.

Introduction

Type 2 diabetes (T2D) has emerged as a major health problem worldwide (1). In addition to other pathophysiological features, T2D is characterized by an increase in hepatic glucose production (HGP) (2–4). Some antidiabetic drugs, such as metformin, exert their therapeutic actions by inhibiting HGP increases (3). To stimulate the development of novel therapeutic agents that target pathologically elevated HGP, it is critical to gain a better understanding of the molecular pathways that regulate hepatic glucose fluxes.

Hepatocyte function is regulated by the activity of cell-surface receptors that belong to the superfamily of GPCRs (5). In general, GPCRs are linked to distinct families of heterotrimeric G proteins (primarily $G_s$, $G_i$, and $G_q$; representative GPCRs: glucagon, $\alpha_2$-adrenergic, and CB1 cannabinoid receptors, respectively). The important metabolic roles of hepatic glucagon receptors in maintaining normoglycemia under fasting conditions and in raising blood glucose levels in response to hypoglycemia are well recognized (6–8). The glucagon receptor (GCGR), which is abundantly expressed in hepatocytes, is linked to the stimulatory G protein $G_s$, which in turn activates adenylyl cyclase to promote the generation of cAMP (6, 9). This signaling pathway ultimately stimulates both glycogenolysis and gluconeogenesis (6), leading to a pronounced increase in HGP. Interestingly, glucagon levels are inappropriately elevated in patients suffering from T2D, suggesting that increased signaling through hepatic GCGRs may play a central role in the pathophysiology of T2D (4, 8).

In most tissues or cell types, the ability of $G_i$-coupled receptors to stimulate adenylyl cyclase is counteracted by the activity of GPCRs that are linked to G proteins of the $G_i$ family that directly inhibit adenylyl cyclase function (10). Hepatocytes express a number of $G_i$-coupled receptors including the $\alpha_2$-adrenergic (11) and CB1 cannabinoid receptors (12, 13). We therefore hypothesized that receptor-mediated activation of hepatocyte $G_i$ signaling pathways might prove useful in reducing the exaggerated hepatic GCGR activity that is characteristic of T2D. However, like virtually all other GPCRs, hepatic $G_i$-linked receptors are also expressed in many other tissues and cell types (14). For this reason, it is impossible to assess the in vivo roles of hepatic $G_i$-coupled receptors by simply administering receptor subtype-selective agonists or antagonists.

To circumvent these difficulties, we used a chemogenetic strategy that involves the use of a designer GPCR (designer receptor exclusively activated by a designer drug [DREADD]) that is selectively linked to $G_i$-type G proteins (15, 16). This designer GPCR (known as hM4Di and referred to herein as Di) represents a mutant M4 muscarinic receptor that no longer binds its endogenous agonist, acetylcholine, but can be selectively activated by clozapine-N-oxide (CNO), a compound that
is otherwise pharmaceutically inert (15, 16). We demonstrate that activation of G i-type G proteins in hepatocytes greatly enhances HGP, resulting in a profound impairment in glucose homeostasis. In contrast, mice lacking functional G i in hepatocytes show the opposite phenotype and are protected against obesity-associated deficits in glucose homeostasis. We also delineate a ROS-dependent pathway through which hepatocyte G i signaling stimulates glucose output from the liver. These surprising new findings could pave the way for the development of novel antidiabetic drugs.

Results

Generation of mice expressing the G i DREADD Di in hepatocytes. To achieve selective expression of Di in hepatocytes, we injected 8-week-old WT male mice (C57BL/6 strain; Taconic) with an adeno-associated virus (AAV) coding for the Di designer receptor (AAV-TBG-Di; 1 × 1011 infectious particles/mouse) via the tail vein. Quantitative reverse transcription PCR (qRT-PCR) studies demonstrated that this procedure resulted in a liver-specific expression of Di (Supplemental Figure 1A; supplemental material available online with this article; https://doi.org/10.1172/JCI94505DS1)

Figure 1. In vivo metabolic studies in Hep-Di mice, which selectively express the Di designer receptor in hepatocytes. (A–F) In vivo metabolic tests performed using Hep-Di mice and control littermates (CTR) treated with the AAV-TBG-EGFP control virus. (A and B) CNO challenge tests. Mice that had free access to food (fed) (A) or had been fasted overnight for approximately 12 hours (fasted) (B) were injected with CNO (10 mg/kg i.p.) or vehicle, followed by monitoring of blood glucose levels. (C) IGTTS (2 g glucose/kg i.p.). (D) PTT (2 g sodium pyruvate/kg i.p.). (E) ITTS (0.75 U insulin/kg i.p.). (F) Glucagon challenge test (16 μg glucagon/kg i.p.). (G–J) Effect of CNO on hepatic glucose fluxes in conscious Hep-Di mice in vivo. (G) Changes in arterial blood glucose levels and rates of (H) glucose appearance (endogenous glucose production [Endo-Ra]), (I) hepatic glycogenolysis, and (J) gluconeogenesis following CNO (10 mg/kg i.v.) treatment of Hep-Di and control mice. All experiments were carried out with chronically catheterized, conscious mice, as described in detail in Methods. After a 5-hour fast, mice were injected with CNO (10 mg/kg) at t0. Mice were maintained on regular chow. All studies were performed using 11- to 16-week-old male mice. Data represent the mean ± SEM (n = 6–8 mice/group). *P < 0.05, **P < 0.01, and ***P < 0.001 versus the corresponding control value. Significance was determined by (A–F) 2-way ANOVA followed by Bonferroni’s post-hoc test and (G–J) 2-tailed Student’s t test.
However, Hep-Di hepatocytes responded normally to arginine vasopressin (AVP), which triggers increases in \([\text{Ca}^{2+}]_i\) by activating endogenous G\(_{q}\)-coupled V\(_1\) vasopressin receptors (18) (Supplemental Figure 2C). These data demonstrated that the Di designer receptor had the predicted signaling profile when expressed in mouse hepatocytes.

In vivo metabolic studies with Hep-Di and control mice. We next subjected Hep-Di and control mice to a series of in vivo metabolic tests. Strikingly, treatment of Hep-Di mice with a single dose of CNO (10 mg/kg i.p.) led to a pronounced increase in blood glucose levels, in both mice that had free access to food and those that had been fasted overnight for approximately 12 hours (Figure 1, A and B). We did not observe this effect in saline-treated Hep-Di mice or in control mice that had received either saline or CNO (Figure 1, A and B).

In an i.p. glucose tolerance test (IGTT), we found that CNO treatment (10 mg/kg i.p.) of control mice had no significant effect on blood glucose excursions as compared with saline-injected control or Hep-Di mice (Figure 1C). On the other hand, CNO administration led to a significant impairment in glucose tolerance in Hep-Di mice (Figure 1C). These CNO-induced deficits in glucose tolerance were not due to changes in glucose-induced insulin secretion (Supplemental Figure 3).

We obtained similar results when we performed a pyruvate challenge test, which is commonly used to study gluconeogenesis in vivo. Combined treatment of Hep-Di mice with sodium pyruvate (2 g/kg i.p.) and CNO (10 mg/kg i.p.) led to greatly

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Figure 2. In vivo metabolic studies in mice Hep-Go–KO mice, which lack functional G\(_i\)-type G proteins in hepatocytes. (A) CNO-induced increases in blood glucose levels in Hep-Di mice required functionally intact hepatic G\(_i\). Mice of the indicated genotypes were fasted for 4 hours, followed by an i.p. injection of CNO (10 mg/kg) and monitoring of blood glucose levels. Studies were conducted using 12-week-old female mice consuming regular chow (RC). (B and D) IGTTs. Hep-Gi–KO mice and their control littermates were maintained on either RC (B) or a HFD (RC, 2 g glucose/kg; HFD, 1 g glucose/kg) (D). (C and E). PTTs (2 g sodium pyruvate/kg i.p.). Mice of the indicated genotypes were maintained on either RC (C) or a HFD (E). IGTTs and PTTs were performed in male mice that were at least 14 weeks old. Data represent the mean ± SEM (RC, n = 9 or 10 mice/group; HFD, n = 5 or 6 mice/group). *P < 0.05, **P < 0.01, and ***P < 0.001, compared with the corresponding control group. Statistical significance was determined by (A) 1-way ANOVA followed by Bonferroni’s post-hoc test and (B–E) 2-tailed Student’s t test.
We next examined whether the Di-mediated increases in blood glucose levels were dependent on intact glucagon signaling. To address this question, we treated Hep-Di and control mice with the anti-GCGR antibody mAB7.44 (10 mg/kg i.p.) (19) 24 hours prior to CNO or glucagon injections. Control experiments showed that pretreatment of Hep-Di mice with the anti-GCGR antibody completely abolished glucagon-induced (16 μg/kg i.p.) hyperglycemic effects (Supplemental Figure 4A). On the other hand, administration of the anti-GCGR antibody had little or no effect on CNO-mediated (10 mg/kg i.p.) increases in blood glucose levels in Hep-Di mice (Supplemental Figure 4B). These data clearly indicate that Di signaling stimulates hepatic glucose release in a glucagon/GCGR-independent fashion.

Quantification of hepatic glucose fluxes in Hep-Di mice. In order to quantify hepatic glucose fluxes, we conducted isotope labeling studies using chronically catheterized, conscious Hep-Di mice.
by injecting an AAV coding for Cre recombinase (AAV-TBG-CRE) into the tail vein of ROSA26 PTX mice (24). In this latter mouse strain, the coding sequence of the S1 catalytic subunit of pertussis toxin (S1-PTX) is preceded by a floxed silencer cassette (24) (note that PTX leads to the functional inactivation of Gi-type G proteins via ADP ribosylation). This strategy led to the selective expression of S1-PTX in hepatocytes (Supplemental Figure 5A). For the sake of simplicity, we refer here to these mice simply as Hep-Gi–KO mice. The livers from Hep-Gi–KO mice appeared histologically normal and showed no signs of hepatotoxicity (data not shown). Importantly, we found that the ability of CNO (10 mg/kg i.p.) to induce pronounced hyperglycemic effects was greatly diminished in Hep-Gi–KO mice expressing Di in a hepatocyte-specific fashion (Hep-Di/Gi–KO mice; Figure 2A). This observation indicates that the in vivo metabolic impairments caused by Di signaling in hepatocytes are indeed dependent on the activation of Gi-type G proteins.

IGTTs and pyruvate tolerance tests (PTTs) also showed that Hep-Gi–KO mice had significantly reduced blood glucose excursion (see Methods) (20–22). After fasting the mice for 5 hours, [6,6-2H]glucose was infused continuously into the jugular vein used to measure the rate of glucose appearance (Ra). Total body water was enriched with D2O, from which the contribution of gluconeogenesis and glycogenolysis to Ra was estimated (23). After assessment of baseline glucose enrichment, the Hep-Di and control mice received a bolus of CNO (10 mg/kg i.v.). CNO treatment of Hep-Di mice, but not control mice, led to a rapid and sustained increase in arterial glucose concentrations and Ra (Figure 1, G and H). The CNO-mediated increase in Ra (Figure 1H) was due to significant and sustained increases in the rates of both gluconeogenesis and glycogenolysis (Figure 1, I and J). In vivo metabolic studies in mice lacking functional Gi in hepatocytes. The metabolic phenotypes of the CNO-treated Hep-Di mice suggested that inhibition of hepatic Gi signaling might prove useful to reduce pathologically enhanced HGP. To explore this possibility, we generated mutant mice that lacked functional Gi-type G proteins selectively in hepatocytes. These mice were obtained by injecting an AAV coding for Cre recombinase (AAV-TBG-CRE) into the tail vein of ROSA26 PTX mice (24). In this latter mouse strain, the coding sequence of the S1 catalytic subunit of pertussis toxin (S1-PTX) is preceded by a floxed silencer cassette (24) (note that PTX leads to the functional inactivation of Gi-type G proteins via ADP ribosylation). This strategy led to the selective expression of S1-PTX in hepatocytes (Supplemental Figure 5A). For the sake of simplicity, we refer here to these mice simply as Hep-Gi-KO mice. The livers from Hep-Gi-KO mice appeared histologically normal and showed no signs of hepatotoxicity (data not shown).

Importantly, we found that the ability of CNO (10 mg/kg i.p.) to induce pronounced hyperglycemic effects was greatly diminished in Hep-Gi-KO mice expressing Di in a hepatocyte-specific fashion (Hep-Di/Gi-KO mice; Figure 2A). This observation indicates that the in vivo metabolic impairments caused by Di signaling in hepatocytes are indeed dependent on the activation of Gi-type G proteins. IGTTs and pyruvate tolerance tests (PTTs) also showed that Hep-Gi-KO mice had significantly reduced blood glucose excursion.
sions as compared with control littersmates injected with the AAV-
TBG-GFP virus (Figure 2, B–E). We observed that these effects
were independent of the type of diet that the mice consumed
(regular chow or a high-fat diet [HFD]). Importantly, in the HFD
feeding studies, the metabolic deficits observed with control mice
(glucose intolerance and enhanced in vivo gluconeogenesis) were
absent in the Hep-Gi–KO mice (Figure 2, D and E). Body weights
and blood glucose and plasma insulin levels were not significantly
different between the HFD Hep-Gi–KO and HFD control mice
(Supplemental Figure 5B).

Glucose output studies with primary Hep-Di hepatocytes. To con-
firm that the Di-mediated impairments in glucose homeostasis
observed in vivo were indeed caused by altered hepatic glucose fluxes,
we performed studies using primary hepatocytes isolated from
Hep-Di mice (Hep-Di hepatocytes). We treated Hep-Di hepatocytes
with either glucagon (100 nM), as a positive control, or CNO
(10 μM), either in the absence or presence of PTX (300 ng/ml). We
found that CNO treatment of Hep-Di hepatocytes stimulated glu-
cose output in a fashion similar to that seen with glucagon (Figure
3A). Importantly, the stimulatory effect of CNO, but not that of glu-
cagon, was completely abolished in the presence of PTX (Figure 3A).
These observations strongly support the concept that Di-mediated
stimulation of HGP depends on the activation of G_i-type G proteins.

ERK activation does not contribute to Di-stimulated HGP. Many
studies have shown that G_i-coupled receptors can stimulate dif-
f erent MAPK signaling pathways, including the ERK and JNK
signaling cascades (25–28). Given the important roles of acti-
vated MAPKs in regulating HGP (29–33), we hypothesized that
MAPK-dependent signaling might contribute to the Di-mediated
changes in hepatic glucose fluxes. Initially, we demonstrated that
CNO (10 μM) treatment of Hep-Di hepatocytes led to a significant
stimulation of ERK1/2 phosphorylation (Supplemental Figure 6,
A and B). This effect was abolished in the presence of PTX (300
ng/ml) (Supplemental Figure 6, A and B), which is indicative of
the involvement of G_i-type G proteins. To test the hypothesis that
increased ERK1/2 phosphorylation was required for Di-mediated
changes in HGP, we performed glucose output assays using iso-
lated Hep-Di hepatocytes. Pretreatment with U0126 (10 μM), a
selective MEK inhibitor that prevents ERK1/2 phosphorylation,
did not impair the ability of CNO (10 μM) or glucagon (100 nM) to

Figure 5. In vivo and in vitro studies with CB1 cannabinoid receptor agonists. (A and B) ICTTs in control and Hep-Gi–KO mice. Note that AEA caused
impaired glucose tolerance in control mice (A) but not in Hep-Gi–KO mice (B). Mice were fasted overnight for approximately 12 hours. Ten minutes before
glucose injections (2 g/kg i.p.), mice were injected with either AEA (10 mg/kg i.p.) or vehicle (Veh). Studies were performed with female mice (at least 16
weeks of age). Data represent the mean ± SEM (n = 4 or 5 mice/group). *P < 0.05, compared with the vehicle-treated group. Statistical significance was
determined by Student’s t test. (C–F) Stimulation of WT mouse primary hepatocytes with CB1 receptor agonists. Hepatocytes were prepared from male
WT mice (~14 weeks of age) maintained on an HFD to boost CB1 receptor expression levels (13). (C and D) Treatment of WT mouse hepatocytes with M-AEA
(150 nM), a metabolically stable CB1 receptor agonist. The agonist-induced increase in glucose output was completely absent in the presence of the ROS
scavenger NAC (5 mM) or the selective JNK inhibitor BI87G3 (10 μM). (E and F) Incubation of WT mouse hepatocytes with HU210, a CB1 receptor agonist.
Hepatocytes were pretreated with NAC (5 mM) for 2 hours and then stimulated with HU210 (1 μM) for the indicated durations. Subsequently, p-JNK and
total JNK expression levels were determined by Western blotting. (E) Representative Western blot. (F) Quantification of Western blot data. Immunoreactive
bands were quantified using ImageJ. p-JNK expression levels were normalized to total JNK expression. Data represent the mean ± SEM from 3 independent
experiments. *P < 0.05, **P < 0.01, and ***P < 0.001, compared with the corresponding control value. Statistical significance was determined by (A and B)
2-tailed Student’s t test and (C, D, and F) 2-way ANOVA followed by Bonferroni’s post-hoc test). See complete unedited blots in the supplemental material.
promote glucose release from Hep-Di hepatocytes (Supplemental Figure 6C). Thus, it is unlikely that Di-induced ERK phosphorylation contributes to the impairments in glucose homeostasis triggered by stimulation of hepatic Gί signaling.

**Critical role of JNK activation in mediating Di-stimulated HGP.** We found that CNO treatment (10 μM) of Hep-Di hepatocytes also led to a significant stimulation of JNK phosphorylation, in a PTX-sensitive manner (Figure 3B). Strikingly, CNO-induced stimulation of glucose release from Hep-Di hepatocytes, but not the corresponding glucagon response, could be totally blocked by BI87G3 (10 μM), a selective JNK inhibitor (Figure 3C). Consistent with these in vitro data, we observed that CNO treatment (10 mg/kg i.p.) of Hep-Di mice also resulted in a significant increase in hepatic JNK phosphorylation (Figure 3D).

To further confirm the importance of JNK signaling in Di-mediated hyperglycemic responses in vivo, we generated mice expressing a dominant-negative version of JNK (JNK-DN) selectively in hepatocytes of Hep-Di mice (Hep-Di-JNK–DN mice). These mice were generated by injecting an adenovirus coding for JNK-DN (34) into the tail vein of Hep-Di mice. A CNO challenge test showed that CNO-induced (10 mg/kg i.p.) increases in blood glucose levels were significantly reduced in Hep-Di-JNK–DN mice as compared with Hep-Di mice (Figure 3E), indicating that JNK activation plays a key role in mediating Gί-dependent hyperglycemic responses in vivo. CNO-induced blood glucose elevations were greatly reduced but not abolished in Hep-Di-JNK–DN mice (Figure 3E). One possible explanation for this finding is that other signaling pathways, besides the JNK cascade, contribute to Gί-mediated increases in HGP. Alternatively, it is possible that the JNK-DN construct was unable to suppress hepatic JNK signaling completely.

Activation of hepatic JNK signaling modulates the expression of genes regulating hepatic glucose fluxes, including G6Pase and PEPCK, the 2 rate-controlling enzymes in the process of gluconeogenesis. Consistent with this notion, CNO treatment (10 mg/kg i.p.) of Hep-Di mice increased the hepatic expression of these 2 key enzymes (Supplemental Figure 7A). Studies with isolated Hep-Di hepatocytes showed that selective inhibition of JNK by BI87G3 (10 μM) drastically reduced CNO-induced increases in G6Pase expression (Supplemental Figure 7B).

Since enhanced JNK activity has been linked to impaired insulin receptor signaling in various cell types (32, 35), we studied insulin-induced (10 nM) AKT and ERK phosphorylation in isolated Hep-Di hepatocytes, in the absence or presence of CNO (10 μM). Western blot studies demonstrated that insulin-mediated increases in AKT and ERK phosphorylation were not reduced upon costimulation of Hep-Di hepatocytes with CNO (Supplemental Figure 8). This observation strongly suggests that activation of Gί-type G proteins promotes hepatic glucose release independently of insulin receptor signaling.

**Inhibition of the PI3K pathway does not affect Di-dependent activation of HGP.** Since Gί signaling can also stimulate the PI3K pathway (36, 37), we studied the possible contribution of this pathway to Di-mediated increases in HGP. Specifically, we measured CNO-induced glucose output from Hep-Di hepatocytes in the absence or presence of LY294002 (20 μM), a selective PI3K inhibitor. We found that the presence of the PI3K inhibitor had no significant effect on CNO-induced glucose release (Supplemental Figure 9), suggesting that the PI3K pathway does not make a significant contribution to the Di-mediated increase in HGP.

**Hepatocyte Di signaling promotes oxidative phosphorylation and ROS production.** We designed a series of experiments to elucidate the pathway that links hepatic Gί signaling to JNK activation. JNKs are activated by various stress stimuli that produce ROS (38). In agreement with this notion, we found that CNO (10 μM) treatment of Hep-Di hepatocytes triggered pronounced increases in ROS production in a time-dependent and PTX-sensitive (300 ng/ml) fashion (Figure 4A), indicating that activation of Gί-type G proteins stimulates ROS accumulation in hepatocytes. Interestingly, pretreatment of Hep-Di hepatocytes with N-acetyl cysteine (NAC) (5 mM), a ROS scavenger, completely blocked CNO-induced (10 μM) JNK phosphorylation increases (Figure 4B).

We next hypothesized that Di-mediated ROS formation was triggered by an increase in the rate of mitochondrial oxidative phosphorylation (39). To address this question, we measured the CNO-induced oxygen consumption rate (OCR) of Hep-Di hepatocytes by using Seahorse technology. Strikingly, CNO (10 μM) treatment of Hep-Di hepatocytes (Figure 4C), but not of control hepatocytes (Figure 4D), strongly increased basal respiration in a PTX-sensitive fashion.
To further strengthen the link between Di-mediated increases in ROS production and enhanced HGP, we treated Hep-Di hepatocytes with the ROS scavenger NAC (5 mM), either in the absence or presence of CNO 10 μM or glucagon (100 nM). Strikingly, we observed that the CNO-induced increase in glucose output, but not the corresponding glucagon response, was completely blocked in the presence of NAC (Figure 4E).

Taken together, these data indicate that activation of hepatic G_i signaling stimulates the OCR, resulting in increased ROS production and activation of JNK, which eventually stimulates HGP.

RNA-sequencing analysis of hepatic gene expression following CNO treatment of Hep-Di mice. While we demonstrated that intact JNK signaling is required for maximal glucose output after stimulation of hepatic G_i signaling, other pathways may also contribute to this response, as suggested by the data in Figure 3E. To obtain information about such non-JNK-dependent pathways, we studied changes in hepatic gene expression in an unbiased fashion using RNA-sequencing (RNA-seq) analysis. We prepared liver RNA from Hep-Di mice 30 minutes after injection with either CNO (10 mg/kg i.p.) or saline (control) and then subjected these RNA samples to RNA-seq analysis. Gene expression analysis showed that CNO treatment of Hep-Di mice led to the differential expression of more than 1,000 hepatic genes (Supplemental Figure 10 and Supplemental Table 3). Interestingly, many genes associated with increased ER stress and the linked unfolded protein response (UPR) were upregulated after activation of hepatic Di signaling (Supplemental Figure 10B). It is well known that ER stress and the resulting UPR promote ROS production and JNK activation (32, 40, 41), as observed in the present study. The CNO group also displayed altered expression levels of many genes involved in activation of the Nrf2/antioxidant response element signaling pathway, a major mechanism in the cellular defense against oxidative stress (Supplemental Figure 10B) (40). Stimulation of hepatic Di signaling also enhanced the expression of several genes involved in the p38/MAPK signaling pathway (Supplemental Figure 10B). This observation is of particular interest, since activation of p38 has been linked to elevated hepatic gluconeogenesis (42). On the basis of these results, it is likely that other cellular pathways, besides JNK-induced signaling, also contribute to the observed increases in G_i-mediated HGP. The precise nature and relative contribution of these additional, non-JNK pathways to the observed metabolic phenotypes will be the subject of future studies.

Activation of a G_i-coupled receptor endogenously expressed by hepatocytes. Hepatocytes express a number of endogenous G_i-coupled receptors including a_2A-adrenergic (11) and CB_1 cannabinoid receptors (12, 13). Interestingly, recent studies have shown that mice lacking CB_1 receptors selectively in hepatocytes show significant improvements in glucose homeostasis in various metabolic assays (12, 13). Consistent with this observation, we found that injection of control mice with anandamide (AEA) (10 mg/kg i.p.), a cannabinoid receptor agonist, led to markedly impaired glucose tolerance (IGTT; Figure 5A). Importantly, this AEA effect was absent in Hep-Gi–KO mice (Figure 5B), strongly supporting the concept that AEA-induced glucose intolerance is caused by G_i signaling triggered by activated hepatic CB_1 receptors.

To demonstrate that hepatic CB_1 receptors were able to activate a signaling pathway similar to that of the Di designer receptor, we carried out additional functional assays with WT mouse hepatocytes. To increase CB_1 receptor expression levels, hepatocytes were obtained from mice that had been maintained on a HFD (13). As observed with CNO-treated Hep-Di hepatocytes, treatment of WT hepatocytes with a CB_1 receptor agonist (150 nM methanandamide [M-AEA]) caused a significant increase in glucose output (Figure 5, C and D). Strikingly, this response was completely absent in the presence of the ROS scavenger NAC (5 mM) or the selective JNK inhibitor BI877G3 (10 μM) (Figure 5, C and D, respectively). As expected, CB_1 receptor activation (agonist: HU210, 1 μM) caused significant, time-dependent increases in JNK phosphorylation (Figure 5, E and F) that were not observed in NAC-treated (5 mM) hepatocytes (Figure 5, E and F). Taken together, these data strongly support the concept that activation of endogenous hepatocyte CB_1 receptors, like stimulation of hepatic Di signaling, promotes ROS formation, resulting in the activation of JNK and enhanced hepatic glucose production.

Altered gene expression in livers prepared from fasted WT mice. We next examined hepatic gene expression levels in fasted WT mice. qRT-PCR studies showed that the hepatic expression levels of G_i and the G_i-coupled a_2A-adrenergic receptor were significantly increased in mice after a 16-hour fast (Supplemental Figure 11). These findings are consistent with the concept that enhanced hepatic G_i signaling plays a role in promoting HGP under physiological conditions.

G_i signaling stimulates glucose release in human hepatocytes. To study whether increased G_i signaling also led to enhanced HGP in human liver, we transduced human primary hepatocytes with an adenoavirus coding for a constitutively active version of G_i2 (CA-Gi) (43). We found that human CA-Gi hepatocytes had a significant increase in glucose output (Figure 6A). This CA-Gi-dependent effect was abolished in the presence of NAC (5 mM), strongly suggesting that G_i stimulates HGP via a similar signaling pathway in mouse and human hepatocytes. Moreover, human CA-Gi hepatocytes showed significant increases in JNK phosphorylation and G6Pase transcript levels (Figure 6, B and C), consistent with the data obtained in mouse hepatocytes.

Altered gene expression in hepatic tissue from patients with nonalcoholic steatohepatitis. We also performed gene expression analyses using RNA prepared from the livers of patients with nonalcoholic steatohepatitis (NASH) and from healthy controls. Except for 1 individual, 14 of the 15 patients with NASH showed clear signs of insulin resistance (Supplemental Table 2). Consistent with this observation, NASH is known to be strongly correlated with hepatic insulin resistance (44, 45). Interestingly, qRT-PCR studies showed that the hepatic expression levels of the a_2A-adrenergic and CB_1 cannabinoid receptors, 2 prototypical G_i-coupled receptors expressed by hepatocytes (11–14), were greatly increased in NASH patients (Supplemental Figure 12). On the other hand, the hepatic RNA levels of G_i2 and G_i3 were significantly reduced in patients with NASH (Supplemental Figure 12), most likely because of counterregulatory mechanisms caused by enhanced G_i signaling through a_2A-adrenergic and CB_1 receptors and, perhaps, other G_i-coupled receptors.

Discussion
An increase in HGP is one of the key features of T2D (2–4). Previous studies have shown that enhanced hepatic glucagon/GCGGR signaling greatly contributes to this metabolic deficit
(4, 7). Activated GCGRs couple to the stimulatory G protein $G_s$, which in turn activates adenylyl cyclase and PKA, ultimately triggering a series of signaling events that promote glycogen breakdown and gluconeogenesis (6).

In contrast to the GCGR and other $G_s$-coupled receptors, GPCRs that preferentially couple to $G_i$-type proteins are known to inhibit the function of adenylyl cyclase (10). We therefore tested the hypothesis that activation of hepatocyte $G_i$ signaling might represent a new strategy to reduce pathologically enhanced GCGR activity. Hepatocytes express several $G_i$-linked receptors including $\alpha_2$-adrenergic (11) and CB1 cannabinoid receptors (12, 13). However, these receptors, like virtually all other nonsensory GPCRs, are expressed in many other tissues and cell types (14). For this reason, it is not possible to selectively stimulate native $G_i$-coupled receptors in hepatocytes by simply administering receptor-selective agonists in vivo. To circumvent this limitation, we took advantage of the availability of a new class of designer GPCRs known as DREADDs (15, 16, 46). Importantly, DREADDs do not bind any endogenous ligands but can be selectively activated by CNO, a synthetic drug that is otherwise pharmacologically inert (15, 16, 46).

In the present study, we used a viral delivery strategy to selectivity express Di, a $G_i$-coupled DREADD (15, 16), in mouse hepatocytes. In vitro studies with isolated hepatocytes demonstrated that CNO-mediated activation of Di signaling inhibited GCGR-mediated increases in cAMP levels (Supplemental Figure 2A), as expected for a $G_i$-coupled receptor. However, in contrast to our initial hypothesis, CNO treatment of isolated Di hepatocytes promoted HGP (Figure 3A). This effect was abolished in the presence of PTX (Figure 3A), indicating the involvement of $G_i$ proteins of the $G_i$ family.

In agreement with the in vitro studies, in vivo studies in both fed and fasted mice showed that activation of hepatic Di signaling caused pronounced increases in blood glucose levels, impaired glucose tolerance, and increased blood glucose excursions in a PTT (Figure 1, A–D). Moreover, the hyperglycemic effects of exogenously administered glucagon were further enhanced after treatment of Hep-Di mice with CNO (Figure 1F). Quantification of hepatic glucose fluxes in conscious Hep-Di mice revealed that CNO-mediated activation of hepatic $G_i$ signaling resulted in significant increases in both the rate of glycogen breakdown and gluconeogenesis (Figure 1, I and J), indicating that both of these processes contribute to $G_i$-mediated stimulation of HGP in vivo.

By using a mouse model lacking functional $G_i$ proteins selectively in hepatocytes, we demonstrated that the hyperglycemic effects mediated by activation of hepatic Di signaling caused pronounced increases in blood glucose levels, impaired glucose tolerance, and increased blood glucose excursions in a PTT (Figure 1, A–D). Moreover, the hyperglycemic effects of exogenously administered glucagon were further enhanced after treatment of Hep-Di mice with CNO (Figure 1F). Quantification of hepatic glucose fluxes in conscious Hep-Di mice revealed that CNO-mediated activation of hepatic $G_i$ signaling resulted in significant increases in both the rate of glycogen breakdown and gluconeogenesis (Figure 1, I and J), indicating that both of these processes contribute to $G_i$-mediated stimulation of HGP in vivo.

To demonstrate that our findings are also applicable to $G_i$-coupled receptors that are endogenously expressed by hepatocytes, we further analyzed signaling through hepatocyte CB$_1$ cannabinoid receptors (12, 13). Consistent with the outcome of a previous study (12), acute i.p. treatment of WT mice with AEA, a cannabinoid receptor agonist, caused severely impaired glucose tolerance (Figure 5A). This effect was completely abolished in...
Hep-Gi–KO mice (Figure 5B), indicating that activation of hepatic G_i proteins by an endogenously expressed G_i-coupled receptor also led to deficits in glucose homeostasis in vivo.

We also showed that activation of hepatic CB1 receptors led to enhanced glucose release from hepatocytes via a signaling pathway similar to that stimulated by the Di designer receptor (Figure 5). Thus, these data strongly support the notion that activation of G_i-coupled receptors endogenously expressed by hepatocytes promotes ROS formation, resulting in JNK activation and enhanced HGP.

In summary, we report the surprising finding that activation of hepatic G_i-type G proteins leads to an increase in HGP and a deterioration of glucose homeostasis. On the other hand, selective inactivation of G_i-type G proteins in hepatocytes results in the opposite phenotype of reduced HGP and improved glucose tolerance. We conclude that hepatic G_i signaling represents a physiologically relevant pathway that is critical for regulating whole-body glucose homeostasis and that agents able to suppress hepatocyte G_i signaling (e.g., antagonists of G_i-coupled receptors endogenously expressed by hepatocytes) may be useful as antidiabetic drugs.

Methods

Drugs. CNO was obtained from the NIH as part of the Rapid Access to Investigative Drug Program funded by the National Institute of Neurological Disorders and Stroke (Bethesda, Maryland, USA). [3H]-NMS (85.4 Ci/mmol) was purchased from PerkinElmer Life Sciences. Insulin (human) was obtained from Eli Lilly (Humulin). AEA, R(+)–M-AEA, PTX, and HU210 were obtained from Tocris. LY294002 was purchased from Cell Signaling Technology. All other drugs used were obtained from MilliporeSigma (B187G3, U0126, NAC, atropine sulfate, sodium pyruvate, sodium lactate, glucagon, antimycin A, and rotenone).

Mouse maintenance and diet. Mice were housed in a specific pathogen-free barrier facility and maintained on a 12-hour light/12-hour dark cycle (light period from 6:00 am to 6:00 pm). Mice were provided ad libitum access to water and consumed either standard pathogen–free barrier facility and maintained on a 12-hour light/12-hour dark cycle (light period from 6:00 am to 6:00 pm). Mice were provided ad libitum access to water and consumed either standard

The Journal of Clinical Investigation

Generation of Hep-Gi–KO mice. To selectively inactivate G_i-type G proteins in hepatocytes, we used mice expressing S1-PTX, a known inhibitor of G_i signaling, under the control of the ROSA26 locus in a Cre recombinase–dependent manner (ROSA26^{ERT2} on a C57BL/6J genetic background) (24). In ROSA26^{ERT2} mice, the coding sequence of S1-PTX is preceded by a floxed silencer cassette (24). To achieve selective expression of S1-PTX in hepatocytes, 8-week-old female ROSA26^{ERT2} mice were injected with the AAV-TBG-CRE virus (1 × 10^{11} infectious units). To generate a group of control animals, 8-week-old female ROSA26^{ERT2} mice were treated in the same manner with the AAV-TBG-EGFP control virus. Viruses were delivered via the tail vein suspended in 100 μl saline.

Generation of Hep-JNK-DN and Hep-Di-JNK-DN mice. To obtain Hep-Di mice expressing a DN version of JNK selectively in hepatocytes (Hep-Di-JNK-DN mice), we coinjected 8-week-old male WT C57BL/6 mice (Taconic) with the AAV-TBG-Di virus (1 × 10^{11} infectious units) and an adenovirus coding for a DN version of JNK (Ad-JNK-DN; 1.5 × 10^{11} infectious units) (54). Using the same strategy, we generated Hep-JNK-DN mice by injecting the Ad-JNK-DN virus together with the AAV-TBG-EGFP control virus. Viruses were suspended in 100 μl saline and delivered via the tail vein.

cAMP assay. Primary mouse hepatocytes were suspended at a density of 2 × 10^6 cells per milliliter in phenol red-free Williams’ medium containing 500 μM IBMX. Subsequently, 5-μl aliquots of the cell suspension were added to the wells of a white-bottomed, 384-well plate (-10,000 cells/well). Cells were then incubated for 25 minutes at 37°C in the presence of increasing concentrations of glucagon and a fixed concentration of CNO (10 μM). After this incubation step, cells were lysed, and changes in intracellular cAMP levels were determined by using a FRET-based cAMP Detection Kit (cAMP Dynamic 2 Kit; Cisbio) (50).

Calcium mobilization assay. Primary hepatocytes were plated at a density of 3.5 × 10^4 cells per well in collagen-coated, 96-well, black-walled, clear-bottomed plates (Thermo Scientific) in medium consisting of DMEM containing 10% FBS. Approximately 18 hours later, agonist-mediated changes in 

Radioligand binding studies. Radioligand binding studies were performed with membranes prepared from mouse liver tissue. Liver membranes were obtained as described in detail previously (52). Binding reactions containing approximately 10 μg membrane protein per tube were carried out for 2 hours at 22°C in 0.5 ml binding buffer containing 25 mM sodium phosphate and 5 mM MgCl_2 (pH 7.4). We used 6 different concentrations of the [3H]-NMS radioligand, ranging from 1 to 40 nM. Nonspecific binding was defined as the binding observed in the presence of 10 μM atropine. Binding reactions were terminated by rapid filtration over GF/C Brandel filters, followed by 3 washes with ice-cold distilled water. The amount of radioactivity that remained bound to the filters was determined by liquid scintillation spectrometry. Saturation binding data were analyzed by using GraphPad Prism 4.0 software.

In vivo metabolic tests. Mouse phenotyping studies were initiated 2 weeks after treatment of mice with AAVs or 3 to 5 days after infection with adenoviruses. In vivo metabolic tests were performed with male or female mice (10–20 weeks of age) using standard procedures.
In brief, prior to IGTTs, mice were fasted overnight for approximately 12 hours. Blood glucose concentrations were determined using blood collected from the tail vein immediately before and at defined time points after i.p. injection of glucose (1 or 2 g/kg). For PTTs and ITTs, mice were fasted in the same fashion and then injected i.p. with either sodium pyruvate (2 g/kg) or human insulin (0.75 U/kg; Humulin; Eli Lilly), followed by the monitoring of blood glucose levels. To assess the sensitivity of mice to exogenously administered glucagon, glucagon challenge tests were performed using mice that had ad libitum access to food or had been fasted overnight for approximately 12 hours. Blood glucose levels were determined at various time points after i.p. injection of glucagon (16 μg/kg).

In some of the tests, the mice were injected with the anti-GCGR antibody mAb7zv44 (10 mg/kg i.p.; Genentech) (19) twenty-four hours prior to treatment with CNO (10 mg/kg i.p.) or glucagon (16 μg/kg).

To study glucose-stimulated insulin secretion (GSIS), male Hep-Di and control mice (10–20 weeks of age) were fasted overnight for approximately 12 hours and then coinfected with glucose and CNO (glucose, 2 g/kg; CNO, 10 mg/kg), followed by monitoring of plasma insulin levels.

Blood glucose levels were monitored using an automated blood glucose reader (Glucometer Elite Sensor; Bayer). Plasma insulin levels were determined using an ELISA kit (Crystal Chem Inc.), according to the manufacturer’s instructions.

In vivo analysis of hepatic glucose fluxes. Male Hep-Di mice and control mice (~15 weeks of age) were generated by AAV injections as described in the Generation of Hep-Di mice section. Studies were initiated 2 weeks after viral treatment. Catheters were implanted under isoflurane anesthesia in the right jugular vein and left common carotid artery for infusion of tracers and sampling of blood, respectively (20, 53). Following the surgery, the animals were individually housed and their body weights recorded. Five days after surgery, on the day of the study, the mice were placed in bedded containers (at 7:00 am), and food was removed. Infusion lines were connected through a swivel system to the catheters of unrestrained, conscious mice to allow freedom of movement. At 10:00 am (t₀ min), a bolus of [6,6-D₂]-glucose (80 mg/kg) and D₂O (1.5 mg/kg) were given over a 40-minute period. This was followed by a constant infusion of [6,6-D₂]-glucose (0.8 mg/kg/min) diluted in saline containing 4.5% D₂O that was maintained for the duration of the study. At t₀ minutes and tᵣ minutes, blood samples were taken to assess glucose concentrations and glucose enrichment. At tᵣ minutes, a bolus of CNO (10 mg/kg) was given via the jugular vein catheter. Blood samples were taken every 10 minutes for 50 minutes. Reconstituted red blood cells from a donor mouse were continuously infused (4 μl/min) for the duration of the study.

Glucose isotopomer distribution in arterial plasma was determined in the Vanderbilt Hormone Assay and Analytical Services Core using Agilent 5977A MSD GC/MS (Agilent Technologies) according to the method of Antoniewicz et al. (54) and analyzed using isotopomer computational analysis software (55). Glucose fluxes were assessed using nonsteady-state equations (volume of distribution of glucose= 130 ml/kg) (56, 57). The contribution of gluconeogenesis was assessed as the enrichment ratio of deuterium enrichment on the fifth carbon of glucose/deuterium enrichment on the second carbon of glucose (54, 58).

In vivo studies in AEA-treated mice. Adult female Hep-G2-KO and control mice (at least 16 weeks of age) that had been fasted overnight for approximately 12 hours were injected with AEA (10 mg/kg i.p.), a cannabinoid receptor agonist. AEA was prepared in a saline/DMSO/Tween-80 solution at a ratio of 18:1:1 (12). Ten minutes after AEA treatment, IGTTs were performed as described in the In vivo metabolic tests section.

Isolation and culture of primary mouse hepatocytes. Mice (10- to 18-week-old males) were anesthetized with a single i.p. injection (250–500 mg/kg) of tribromoethanol (Avertin). Primary hepatocytes were then isolated using a 2-step collagenase perfusion protocol (59). Hepatocytes (~0.7 × 10⁶ cells/well) were cultured at 60% to 70% confluence in DMEM (4.5 g/l glucose) containing 10% FBS in collagen I-coated, 6-well plates (Corning). Cells were then further processed for mitochondrial respiration or glucose production assays.

Glucose production studied with primary mouse hepatocytes. Primary mouse hepatocytes (~0.7 × 10⁶ cells/well) were cultured in 6-well plates in medium (phenol red-free DMEM containing 10% FBS and 4.5 g/l glucose) for 4 to 6 hours at 37°C. The medium was then replaced with fresh phenol red-free DMEM containing 1 g/l glucose. Subsequently, hepatocytes were cultured overnight and then washed thoroughly with PBS. To stimulate glucose production, the medium was replaced with glucose- and phenol red-free DMEM supplemented with gluconeogenic substrates (20 mM sodium lactate and 2 mM sodium pyruvate, respectively) in the presence of glucagon (100 nM) or CNO (10 μM) and various inhibitors of distinct signaling pathways. Hepatocytes were incubated at 37°C for 4 hours, after which the culture medium was collected for the measurement of glucose concentrations using a glucose assay kit (MilliporeSigma). Hepatocytes were scraped off the wells with RIPA buffer containing a proteinase inhibitor cocktail from Roche in order to measure total protein per well using the bicinchoninic acid (BCA) method.

Mouse hepatocytes were also stimulated with M-AEA, a stable CB₁ receptor agonist. For this set of experiments, hepatocytes were isolated from WT mice that had been maintained on a HFD for 8 weeks (~12–16 weeks of age). Hepatocytes (~0.5 × 10⁶ cells/well) were cultured overnight in 6-well plates in medium (phenol red-free DMEM containing 10% FBS and 4.5 g/l glucose) at 37°C. Hepatocytes were washed twice with PBS and then incubated with the JNK inhibitor BI87G3 (10 μM) or NAC (5 mM) for 2 hours (the DMSO concentration in the medium was kept at 1%) or were left untreated. Subsequently, hepatocytes were incubated at 37°C for 5 hours in the presence or absence of M-AEA (150 nM) and processed as described above.

Analysis of Gᵢ-mediated glucose output from human hepatocytes. Human primary hepatocytes (Hum4113; Triangle Research Labs) were seeded into collagen I-coated 6-well plates (Corning) at a density of 0.8 × 10⁴ cells per well (Human Hepatocyte Plating Medium; Triangle Research Labs). Six hours later, hepatocytes were transduced with an MOI of 10 (~10 viral particles/cell) of an adenovirus encoding a constitutively active version of Ga₁₅ (CA-GI) (43) in maintenance medium (Hepatocyte Maintenance Medium; Triangle Research Labs). Two hours later, the maintenance medium was replaced with fresh medium. On the next day, glucose output assays were carried out essentially as described in the Hepatic glucose production studied with primary mouse hepatocytes section. Hepatocytes were incubated with gluconeogenic substrates (20 mM sodium lactate and 2 mM sodium pyruvate, respectively) for 1 hour at 37°C.

Preparation of cDNA and qRT-PCR analysis. Using standard molecular techniques, cDNAs were prepared from mouse primary hepatocytes or other mouse tissues (cell types) for qRT-PCR studies (see Supplemental Table 1 for the primer sequences). Total mRNA was
extracted using an RNA kit from QIAGEN, following the manufacturer’s protocol. qRT-PCR studies were conducted as described in detail previously (60). Gene expression data were normalized relative to the expression of β-actin.

**Measurement of hepatocyte mitochondrial OCR.** Measurements of hepatocyte respiration (OCR) were performed using the Seahorse XF24 Analyzer (Seahorse Bioscience). Primary hepatocytes from HepDi or control mice were plated at a density of $4 \times 10^4$ cells per well on collagen I-coated, 24-well Seahorse plates in complete media (phenol red-free DMEM containing 10% FBS and 4.5 g/l glucose), and the media were replaced approximately 6 hours later. On the following day, cells were pretreated with PTX (300 ng/ml) or vehicle for 2 hours. After 3 washes with Seahorse medium, OCR measurements were performed in Seahorse medium supplemented with 2 mM sodium pyruvate and 25 mM glucose, respectively (61). Hepatocytes were stimulated with 10 μM CNO in the presence or absence of PTX (300 ng/ml). Antimycin A and rotenone (5 μM each) were used to inhibit mitochondrial respiration. OCR data were normalized to the protein content per well.

**Analysis of ROS production.** Primary mouse hepatocytes were plated at a density of $3.5 \times 10^4$ cells per well in collagen-coated, 96-well, black-walled, clear-bottomed plates (Thermo Fisher Scientific) in DMEM containing 1 g/l glucose and 10% FBS, in the presence or absence of PTX (300 ng/ml). On the next day, CNO-induced (10 μM) increases in ROS production were measured using the Oxiselect Intracellular ROS Assay Kit (Cell Biolabs) and a Multimode Microplate Reader (Molecular Devices). Experiments were conducted according to the manufacturers’ instructions. All reagents were dissolved in phenol red-free DMEM containing 1 g/l glucose. Increases in ROS accumulation were expressed as changes in fluorescence (peak fluorescence activity minus basal fluorescence activity). Data were analyzed using GraphPad Prism 4.0.

**Western blot studies.** Primary mouse hepatocytes were first cultured in 12-well plates for approximately 6 hours at 37°C in medium (phenol-free DMEM containing 10% FBS and 4.5 g/l glucose). The medium was then replaced with a fresh one, and hepatocytes were cultured overnight. On the next day, hepatocytes were thoroughly washed and treated with CNO (10 μM) and/or insulin (10 nM) at 37°C in a 5% CO2 incubator. In a subset of experiments, cells were preincubated for 2 hours with PTX (300 ng/ml). Incubations were terminated with RIPA buffer containing protease and phosphatase inhibitor cocktails (Roche) at defined time points. Protein lysates were subjected to SDS-PAGE after denaturation of proteins at 95°C. Immunoblot studies were performed using standard procedures (-10 μg protein/lane). Immunoreactive proteins were visualized using SuperSignal West Pico Chemiluminescent Substrate (Pierce, Thermo Fisher Scientific).

We also prepared liver lysates from mice that had been injected with CNO (10 mg/kg i.p.) or vehicle after a 4- to 5-hour fast. Mice were sacrificed 15 minutes after injections. Protein lysates were then subjected to Western blot analysis as described above. The following antibodies, all from Cell Signaling Technology, were used: phosphorylated JNK (p-SAPK/JNK [Thr183/Tyr185], rabbit mAb 4668; 1:1,000 dilution); total JNK (SAPK/JNK antibody 9252; 1:1,000 dilution); p-ERK (p-p44/42 MAPK [Thr202/Tyr204], rabbit mAb 4376; 1:1,000 dilution); total ERK (p-p44/p42 MAPK, ERK1/2 antibody 9102; 1:1,000 dilution); p-AKT (Ser473) (9271; 1:1,000 dilution); and total AKT (9272; 1:1,000 dilution).

**Preparation of human liver RNA and gene expression analysis.** Percutaneous liver biopsies of adult noncirrhotic NASH patients ($n = 15$) were obtained as described previously (62, 63) (for more detailed patient data, see Supplemental Table 2). Control liver biopsies were obtained from 5 nondiabetic patients (mean age, 47 years; $n = 3$ female patients) who had a past history of chronic hepatitis C and were successfully treated with viral eradication at least 6 months prior to the biopsy (64). Histological evaluation of these samples revealed no signs of steatosis or hepatic inflammation or injury.

A 2- to 5-mm sample from the liver biopsy specimen was flash-frozen at the bedside and archived at -80°C. For analysis, samples were homogenized in TRizol (Invitrogen, Thermo Fisher Scientific), and total RNA was extracted according to the manufacturer’s instructions. cDNA was synthesized using the First-Strand cDNA Synthesis System for Quantitative RT-PCR (OriGene), according to the manufacturer’s protocol. Gene expression levels were measured by monitoring SYBR green fluorescence intensity over time using a CFX384 Touch Real-Time PCR System (Bio-Rad). Each PCR reaction (15 μl final volume) consisted of cDNA (15 ng), 7.5 μl of 2x SYBR Green PCR Master Mix (Applied Biosystems), and 100 nM of each PCR primer. For each primer pair, qRT-PCR reactions were performed in triplicate using a 384-well plate format. PCR cycling conditions were as follows: 95°C for 10 minutes, 40 cycles at 95°C for 15 seconds, and 60°C for 1 minute, respectively. The expression of β-actin (ACTB) served as an internal control.

**Statistics.** All data are expressed as the mean ± SEM. Prior to applying specific statistical tests, we performed tests for normality and homogeneity of variance. Data were then tested for statistical significance by 1- or 2-way ANOVA, followed by the post-hoc tests indicated in the figure legends, or by a 2-tailed, unpaired Student’s t test, as appropriate. A P value of less than 0.05 was considered significant.

**Study approval.** All animal studies were approved by the IACUC of the NIDDK, NIH. Studies in humans were approved by the IRB of the NIDDK/NIAMS, and all subjects provided written informed consent.

**Author contributions**

MR, LZ, OPM, and JW designed and conceived the experiments. MR, LZ, SMM, SPP, SJ, LW, YC, RJJ, AHIC, YM, YR, and OPM performed and analyzed the experiments. HK prepared the Ad-JNK–DN virus. MJB provided novel reagents and helpful advice throughout the study. TJC and OPM performed and analyzed the hepatic glucose flux studies. JL and TF supervised and interpreted the OCR experiments. YM and YR generated and provided the human liver cDNA samples. MR, LZ, and JW wrote the manuscript.

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CA-Gi adenosine was provided by Kevin Donahue (University of Massachusetts Medical School, Worcester, Massachusetts, USA). The adenosine coding for GFP (Ad-GFP) was a gift of the laboratory of Marc Montminy (Salk Institute for Biological Studies, La Jolla, California, USA).

Address correspondence to: Jurgen Weiss, Laboratory of Bioorganic Chemistry, Molecular Signaling Section, National Institute of Diabetes and Digestive and Kidney Diseases, Building 8A, Room B1A-05, 8 Center Drive, Bethesda, Maryland 20892, USA. Phone: 301.402.3589; Email: jurgenw@niddk.nih.gov.


