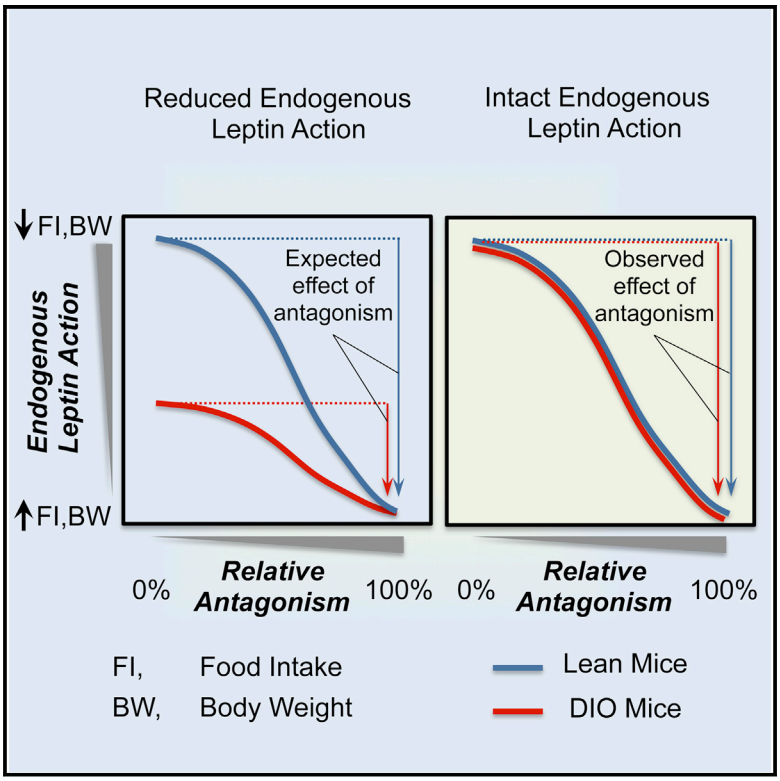
Short Article

Cell Metabolism

Diet-Induced Obese Mice Retain Endogenous Leptin Action

Graphical Abstract



Highlights

- Hyperleptinemic DIO mice maintain leptin-mediated suppression of food intake
- Leptin receptor signaling reacts similarly to the antagonist in lean and DIO mice
- Elevated plasma leptin levels do not reflect a deficit of endogenous leptin action

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In Brief

Hyperleptinemia and reduced response to exogenous leptin suggest impaired leptin action in obesity. By administering a leptin receptor antagonist, Ottaway et al. show comparable control of energy balance by leptin in lean and diet-induced obese mice, suggesting that persistence of obesity is not the result of decreased endogenous leptin action.

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Diet-Induced Obese Mice Retain Endogenous Leptin Action

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SUMMARY

Obesity is characterized by hyperleptinemia and decreased response to exogenous leptin. This has been widely attributed to the development of leptin resistance, a state of impaired leptin signaling proposed to contribute to the development and persistence of obesity. To directly determine endogenous leptin activity in obesity, we treated lean and obese mice with a leptin receptor antagonist. The antagonist increased feeding and body weight (BW) in lean mice, but not in obese models of leptin, leptin receptor, or melanocortin-4 receptor deficiency. In contrast, the antagonist increased feeding and BW comparably in lean and diet-induced obese (DIO) mice, an increase associated with decreased hypothalamic expression of *Socs3*, a primary target of leptin. These findings demonstrate that hyperleptinemic DIO mice retain leptin suppression of feeding comparable to lean mice and counter the view that resistance to endogenous leptin contributes to the persistence of DIO in mice.

INTRODUCTION

Leptin is a 16 kDa hormone secreted by adipocytes (Zhang et al., 1994) that plays a critical role in the control of feeding by acting on specific neurons in the CNS (Myers et al., 2008). Individuals lacking circulating leptin are hyperphagic and obese, features that can be reversed with administration of exogenous leptin (Halaas et al., 1995). In contrast, more common forms of obesity, including diet-induced obesity (DIO), exhibit hyperleptinemia proportional to the amount of body fat stores (Frederich et al., 1995). The inability of high endogenous leptin levels to reduce feeding and mitigate or reverse weight gain is referred to as leptin resistance, and it has been implicitly associated with the impairment of leptin action (Myers et al., 2012). Consistent with this thesis, obese hyperleptinemic animals have a blunted anorectic response to exogenously administered leptin and an associated attenuation of the leptin receptor (LEPR)-dependent intracellular signaling cascade (Enriori et al., 2007).

While the resistance of obese subjects to exogenous leptin has been widely documented, the action of endogenous leptin to control energy balance in obesity has not been rigorously tested. We hypothesized that blockade of the LEPR in mouse models of obesity would give an estimate of endogenous leptin action reflected in changes in food intake and BW. This approach was taken with genetic and diet-induced models of obese mice. Our results demonstrate that despite the presence of hyperleptinemia, wild-type (WT) DIO mice retain a degree of endogenous leptin action similar to that of their lean counterparts. Thus, persistance of obesity in DIO mice occurs despite ongoing endogenous leptin action.

RESULTS

Intraperitoneal PLA Increases Food Intake and Body Weight in Wild-Type Mice, but Not in Mice with Impaired Leptin Signaling

We assessed the in vivo specificity of a pegylated leptin receptor antagonist (PLA) by comparing the effect of daily administration (3 mg/kg intraperitoneal [i.p.], daily) on energy intake and BW in leptin receptor-deficient ($lepr^{dbdb}$, *db*/*db*), leptin-deficient (lep^{obob}, *ob*/*ob*), and age-matched WT control mice over 1 week (Figure 1). Untreated *db*/*db* and *ob*/*ob* mice had significant hyperphagia compared to untreated WT controls (Figure 1A, see also Figure S1A). Consistent with a blockade of endogenous leptin action, PLA significantly increased 1 week energy intake in WT mice. In contrast, PLA failed to increase feeding in *ob*/*ob* or in *db*/*db* mice (Figure 1A). PLA significantly increased BW (Figure 1B) and BW gain (Figure 1C) in lean WT control mice compared to vehicle-treated controls, but failed to affect BW in *db*/*db* mice. Interestingly, there was a small but significant reduction in BW gain in *ob*/*ob* mice treated with PLA (Figure 1C).

Intraperitoneal PLA or Intracerebroventricular LA Increases Food Intake and Body Weight in WT Mice, but Not in Obese Melanocortin 4-Receptor-Deficient Mice

The melanocortin system plays a critical role mediating the effect of leptin on food intake and BW (Seeley et al., 1997). Mice with a homozygous deletion of MC4R ($Mc4r^{-/-}$ mice) are hyperphagic and develop obesity in adulthood that is associated with hyperleptinemia and reduced effectiveness of exogenous leptin (Marsh et al., 1999). To investigate the contribution of MC4R to the actions of endogenous leptin, obese $Mc4r^{-/-}$ mice and WT

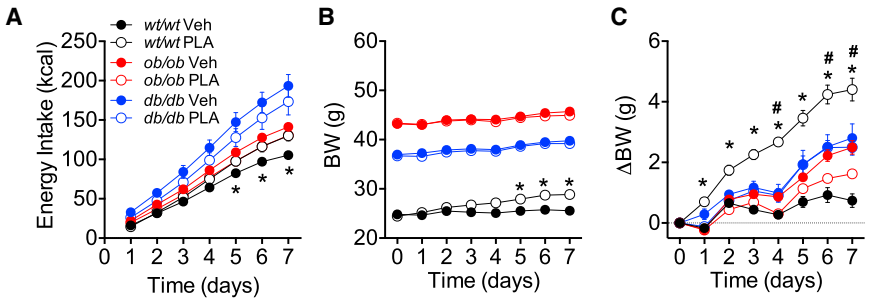

Figure 1. Peripheral Administration of PLA, 3 mg/kg i.p. Once Daily, in Chow-Fed *db/db*, *ob/ob*, or Lean WT Control Mice

(A–C) Daily injection of PLA increases energy intake (A), BW (B), and BW change (C) in lean chow-fed control mice, but not in mice voided of endogenous leptin signaling. Data are shown as mean ± SEM, n = 6. *p < 0.05 WT Veh versus WT PLA; #p < 0.05 *ob/ob* Veh versus *ob/ob* PLA. Two-way repeated-measures (RM) ANOVA followed by Sidak test.

littermates received peripheral PLA (3 mg/kg/day, i.p.) for 1 week. PLA significantly increased energy intake in WT ($p < 0.05$ treatment × time), but not in obese *Mc4r*$^{-/-}$, mice (Figure 2A, see also Figure S1B). 1 week PLA treatment did not affect total BW (Figure 2B) but promoted a significant BW change in WT mice relative to vehicle-treated controls (Figure 2C). In contrast, leptin receptor blockade did not change BW in obese *Mc4r*$^{-/-}$ mice (Figure 2C). PLA was dosed based on BW (1.65-fold difference), but plasma leptin levels were 9.5-fold higher in obese *Mc4r*$^{-/-}$ in comparison to their WT controls (41.34 ± 2.11 versus 4.35 ± 2.46 ng/ml, $p < 0.05$), raising the possibility of insufficient antagonism to counteract the higher levels of endogenous leptin. To ensure maximal reduction of endogenous leptin action, obese *Mc4r*$^{-/-}$ mice and lean WT littermates received an infusion of non-pegylated antagonist (LA, 8 μg/day) for 1 week directly into the lateral cerebral ventricle (intracerebroventricular, i.c.v.) using osmotic minipumps. LA induced significant hyperphagia (Figure 2D, see also Figure S1C) and BW gain (Figures 2E and 2F) in lean WT, but not in obese *Mc4r*$^{-/-}$ mice, despite a trend toward a BW change in the latter ($p = 0.059$, Figure 2F). Since young, preobese *Mc4r*$^{-/-}$ mice retain responsiveness to exogenous leptin (Marsh et al., 1999), we treated a cohort of younger *Mc4r*$^{-/-}$ (28.5 ± 1.5 g) and age-matched WT littermates (24.1 ± 1.0 g) with PLA (3 mg/kg/day, i.p.) for 1 week. PLA did not affect total BW (Figure S1D) but increased the BW gain relative to vehicle-treated controls, as well as energy intake, in *Mc4r*$^{-/-}$ mice ($p < 0.05$ treatment × time; Figures S1E and S1F) and in their WT littermates (Figures S1E–S1G).

Intraperitoneal PLA or Intracerebroventricular LA Increases Food Intake and BW in Lean and DIO Mice

DIO mice are frequently used as a model of leptin resistance. DIO mice and age-matched, chow-fed lean controls were treated with PLA (1, 3, or 10 mg/kg i.p. once daily) for 7 days (lower doses) or 6 days (highest dose). PLA at 1 mg/kg/day significantly increased energy intake in lean mice only (Figure 3A, see also Figure S1H) and did not change BW in lean or DIO mice (Figures 3B and 3C). PLA at 3 mg/kg/day significantly increased food intake (Figure 3B, see also Figure S1I) and total BW (Figure 3E, $p < 0.05$ at day 7) in lean, but not in DIO, mice. However, both lean and DIO mice treated with this dose of PLA exhibited significant BW change when compared to their vehicle controls (Figure 3F), despite a 10-fold increase in circulating leptin in DIO mice compared to lean controls (29.60 ± 2.36 versus 2.94 ± 0.45 ng/ml, $p < 0.05$). PLA at 10 mg/kg/day significantly increased energy intake (Figure 3G, see also Figure S1J) and BW (Figures 3H and 3I) in both lean and DIO mice. To examine near-maximal effects of reducing endogenous leptin action, we infused LA (8 μg/day) i.c.v. into lean and DIO mice for 7 days using osmotic minipumps. Intracerebroventricular LA significantly increased food intake (Figure 3J, see also Figure S1K) in both lean and DIO mice. LA also caused significant differences in total BW (Figure 3K) and relative BW change (Figure 3L) compared to vehicle-treated controls.

When the dose responses of PLA on energy intake and BW change were compared, the effect of endogenous leptin to restrain energy intake was comparable between lean and DIO mice, with the exception of the dose of 3 mg/kg/day (Figure 3M), whereas the BW change compared to vehicle-treated controls were similar in lean and DIO mice with all doses (Figure 3N).

Effect of Reduction of Endogenous Leptin Action on Pomc, Socs3, and Phosphorylated STAT3 Levels in the Arcuate Nucleus of DIO Mice

Expression of two leptin-regulated genes, proopiomelanocortin (*Pomc*) and suppressor of cytokine signaling-3 (*Socs3*), was analyzed in the hypothalamic arcuate nucleus (ARC) following acute or chronic PLA. DIO mice (BW 58.8 ± 1.2 g) received a single dose of PLA (3 mg/kg i.p.) 1 hr prior to the onset of dark. The mice had free access to water and HFD overnight and were euthanized 1 hr after the onset of light. Food intake did not differ during the experimental period (Figure S2A), but PLA-treated mice exhibited a significant BW change in comparison to vehicle-treated controls (Figure S2B), consistent with a reduction in endogenous leptin signaling. Overnight PLA treatment did not affect *Pomc* (Figure 4A) but significantly reduced *Socs3* (Figure 4B) expression in the ARC of DIO mice.

Chronic PLA treatment (3 mg/kg i.p. daily for 7 days; Figures 3D–3F) significantly reduced both *Pomc* (Figure 4C) and *Socs3* (Figure 4D) gene expression in lean and DIO mice. *Pomc* gene expression was similar between lean and DIO mice treated with vehicle (Figure 4C). In contrast, *Socs3* expression was significantly increased in vehicle-treated DIO mice in comparison to vehicle-treated lean controls (Figure 4D).

Levels of phosphorylated signal transducer and activator of transcription-3 (pSTAT3) were analyzed by immunoblot (Figure S3) in the ARC of lean and DIO mice receiving i.c.v. LA (8 μg/day) for 7 days (Figures S2C–S2F). Vehicle-treated DIO mice had increased pSTAT3 in comparison to vehicle-treated lean controls when normalized to beta actin content (Figure 4E). Intracerebroventricular LA significantly reduced pSTAT3 in DIO mice (Figure 4E), and pSTAT3 normalized to total STAT3 content supported this finding ($p = 0.061$, DIO vehicle [Veh] versus DIO LA; Figure 4F).

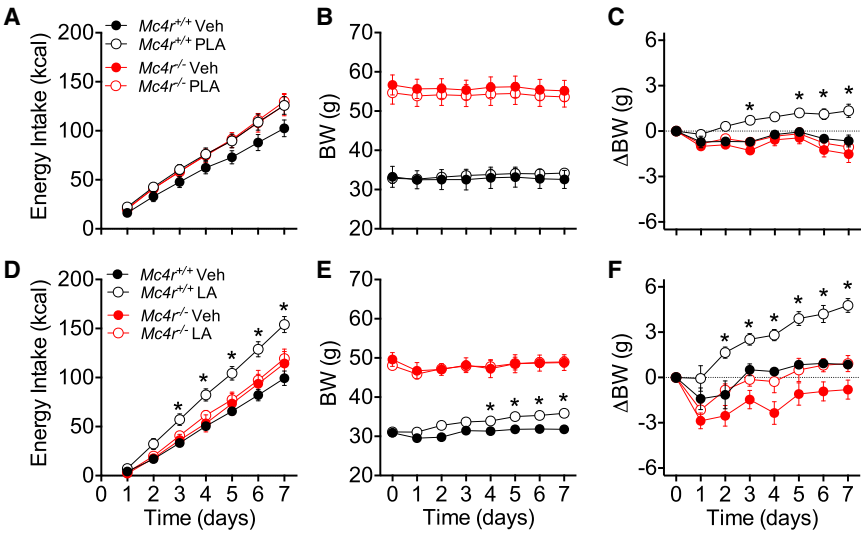

Figure 2. Peripheral Administration of PLA or Central Infusion of LA in Chow-Fed Obese *Mc4r*$^{-/-}$ or WT Littermate Control Male Mice

(A–F) Cumulative energy intake (A and D), BW (B and E), and BW change (C and F) of obese *Mc4r*$^{-/-}$ mice and WT controls receiving either peripheral PLA (3 nmol/kg/day i.p.) (A–C) or central infusion of LA (8 μg/day, i.c.v.) (D–F) for 1 week. Data are shown as mean ± SEM; n = 5–8. *p < 0.05 *Mc4r*$^{+/+}$ Veh versus *Mc4r*$^{+/+}$-treated mice. Two-way RM ANOVA followed by Sidak test.

DISCUSSION

In this study, central or peripheral treatment with a LEPR antagonist (D23L/L39A/D40A/F41A mutant) demonstrates a significant role of endogenous leptin action regulating energy balance. More importantly, our experiments consistently show comparable contribution to the control of BW and suppression of food intake by endogenous leptin in lean and hyperleptinemic DIO mice, regardless of dose and route of administration. These findings in a standard animal model of obesity often cited as leptin resistant indicate that the current view on the role of leptin action in obesity needs revision.

Consistent with our data, peripheral infusion of a different pegylated antagonist (L39A/D40A/F41A mutant) increased feeding in chow-fed mice (Levi et al., 2011). In contrast, central infusion of the non-pegylated L39A/D40A/F41A antagonist failed to increase feeding in chow-fed rats (Tümer et al., 2007). In addition to potential species-specific differences, this discrepancy with our results is likely accounted for by the increased potency of the antagonist used in our experiments, with greater binding to leptin receptor (60-fold) and higher antagonistic activity (14-fold) compared to the L39A/D40A/F41A mutant (Shpilman et al., 2011). This increased potency, combined with the extended duration of action provided by the addition of a polyethylene glycol moiety, provides effectiveness to PLA when admistered peripherally, results that are consistent with earlier reports (Chapnik et al., 2013; Shpilman et al., 2011; Solomon et al., 2014). Despite this increase in potency, PLA lacks orexigenic activity when given to *db*/*db* and *ob*/*ob* mice, which confirms its selectivity in vivo. Indeed, PLA reduces BW gain in *ob*/*ob* mice, which could be the result of weak agonist activity, considering that cytokine receptors such as the LEPR lack intrinsic activity, and their signaling depends on the status of associated kinases (Ishida-Takahashi et al., 2006).

A potential factor previously suggested as contributing to leptin resistance in obesity is the impairment of the transport of leptin through the blood-brain barrier (BBB) into the CNS (Banks et al., 1999; Caro et al., 1996). To circumvent any role of differences in BBB permeability between lean and obese mice, we compared peripheral and i.c.v. administration of high doses of LEPR antagonist. The observation that both lean and DIO mice had comparable increases in energy intake and BW that were proportional to the doses of antagonist administered peripherally or centrally demonstrates that both groups experienced substantial restraint of food intake by endogenous leptin, irrespective of their body weight and adiposity.

Consistent with previous reports (Levi et al., 2011; Solomon et al., 2014), blockade of LEPR signaling in lean, WT mice resulted in significant hyperphagia and BW gain. The lack of effect of PLA to regulate energy balance in LEPR-deficient *db*/*db* mice supports the specificity of PLA for the LEPR and a lack of "off-target" effects in vivo. The dose of PLA given to *db*/*db* mice was less than the maximally effective dose given to DIO animals but was sufficient to induce changes in the BW of high-fat-fed mice. PLA also failed to increase food intake in *ob*/*ob* mice, but it did attenuate their BW gain, suggesting modest LEPR agonism of the compound in this strain, described as having increased leptin sensitivity (Harris et al., 1998).

A key neural circuit involved in the control of energy balance by leptin is the melanocortin system, including direct and/or indirect control of MC4R-expressing neurons by leptin (Ghamari-Langroudi et al., 2011). *Mc4r*$^{-/-}$ mice develop late-onset obesity (Huszar et al., 1997), with hyperleptinemia and resistance to the effect of exogenous administration of leptin (Marsh et al., 1999). The failure of PLA/LA to induce hyperphagia in obese *Mc4r*$^{-/-}$ mice supports a prominent role of the melanocortin system to convey the anorectic action of endogenous leptin in adult mice. This dramatic reduction of leptin action in obese, adult *Mc4r*$^{-/-}$ mice stands in contrast to the maintenance of leptin sensitivity found in young, non-obese mice with *Mc4r* deletion (Marsh et al., 1999) and with the effectiveness of PLA increasing body weight and energy intake in young *Mc4r*$^{-/-}$ mice. This discrepancy suggests an age-dependent convergence from multiple neural circuits toward the melanocortin system as the mediator of leptin effects on the homeostatic control of energy balance. Although this hypothesis remains to be corroborated experimentally, it is supported by considerable evidence suggesting age-dependent changes in leptin action (Gabriely et al., 2002; Morrison et al., 2007; Newton et al., 2013; Scarpace et al., 2000).

The reduced impact of subtracting endogenous leptin action in mouse models of obesity caused by direct (i.e., *db*/*db* or

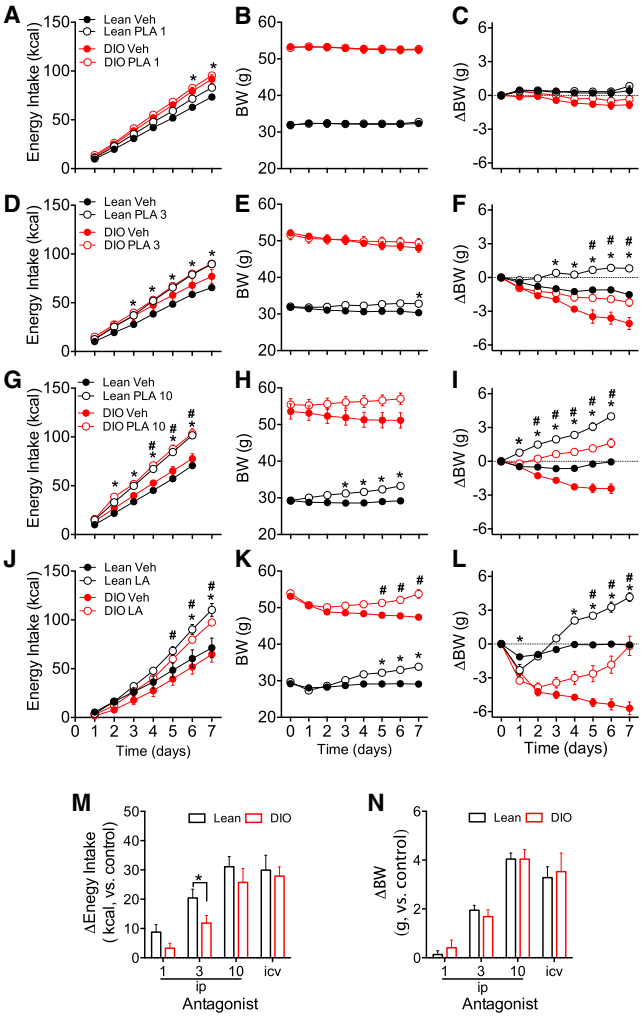

Figure 3. Peripheral Administration of PLA or Central Infusion of LA in Lean and DIO Mice

(A–L) Cumulative energy intake (A, D, G, and J), BW (B, E, H, and K), and BW change (C, F, I, and L) of lean and DIO mice receiving either peripheral PLA (1, 3, 10 nmol/kg/day i.p.) (A–I) or central infusion of LA (8 μg/day, i.c.v.) (J–L). (M and N) Change in caloric intake (M) and BW (N) after 6 days of treatment with either peripheral PLA or central LA.

Data are shown as mean ± SEM n = 7–8 (A–I) or n = 5 (J–L). *p < 0.05 Lean Veh versus Lean PLA; #p < 0.05 DIO Veh versus DIO PLA. Two-way RM ANOVA followed by Sidak test (A–L) or Student's t test (M).

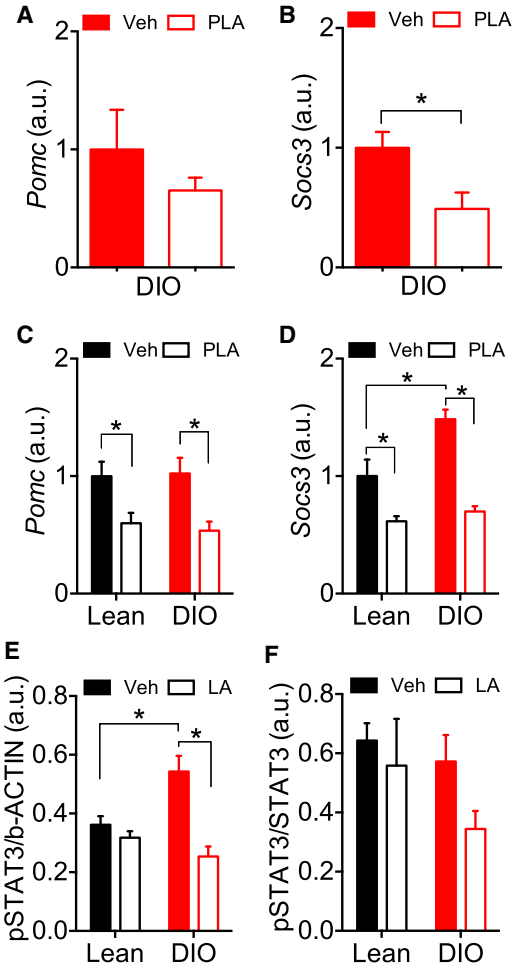

Figure 4. *Pomc* and *Socs3* Gene Expression and pSTAT3 Levels in the Arcuate Nucleus of Mice Treated with Leptin Receptor Antagonist

(A and B) *Pomc* (A) and *Socs3* (B) expression after a single injection of PLA (3 mg/kg i.p.) in DIO mice 1 hr before the onset of the dark phase.

(C and D) *Pomc* (C) and *Socs3* (D) expression after 7 day treatment with PLA (3 mg/kg i.p. once daily) on lean and DIO mice.

(E and F) pSTAT3 levels relative to beta actin (E) and to total STAT3 (F) measured by immunoblot in ARC of lean or DIO mice after 7 day infusion with i.c.v. LA (8 μg/day).

Data are shown as mean ± SEM; n = 5–7; *p < 0.05. Student's t test (B); two-way ANOVA followed by Sidak test (C–E).

ob/ob mice) or indirect (*Mc4r*$^{-/-}$ mice) disruption of leptin signaling provides a striking contrast with the comparable induction of positive energy balance in DIO and age-matched lean mice following the peripheral administration of PLA or central infusion of LA. These findings show that DIO mice maintain intact endogenous leptin action despite hyperleptinemia and support previous observations of the susceptibility of DIO rats to weight gain when given the less-potent leptin receptor antagonist (L39A/D40A/F41A) via i.c.v. (Tümer et al., 2007). In addition to hyperleptinemia, DIO mice exhibit reduced responses to exogenously administered leptin, which has been linked to impairments of the intracellular signaling cascade induced by the activated LEPR (Coppari and Bjørbæk, 2012; Myers et al., 2008). One proposed mechanism of leptin resistance involves reduced LEPR signaling as a result of increased *Socs3* levels (Bjørbaek et al., 1998). Increased *Socs3* prevents the phosphorylation of STAT3 by activated LEPR, providing a means of negative feedback regulation of leptin action in target cells (Myers et al., 2008). Consistent with this view, hyperleptinemic, leptin-resistant DIO mice exhibit increased baseline *Socs3* expression in the ARC (Enriori et al., 2007; Münzberg et al., 2004). Yet, similar to previous studies using DIO mice (Knight et al., 2010; Martin et al., 2006), we observed elevated basal pSTAT3 levels in DIO mice compared to lean controls and a significant decrease with PLA treatment. Since leptin receptor antagonism reduced *Socs3* gene expression, pSTAT3 levels, and the

expression of a target gene, *Pomc* (Münzberg et al., 2003), our data are consistent with the hypothesis that increased *Socs3* and pSTAT3 levels in the ARC of DIO mice are the direct consequence of ongoing endogenous leptin signaling in these obese animals. More importantly, this occurred at doses of antagonist sufficient to elicit similar changes in energy intake and BW in lean and DIO mice. Thus, although the increase in baseline *Socs3* levels exhibited by DIO mice may attenuate the effect of exogenously administered leptin, explaining the lack of expected hypophagia or activation of LEPR signaling cascade, our results suggest that DIO mice do not experience reduced endogenous leptin action and in fact demonstrate that it plays a critical role preventing further BW gain.

Our results suggest that DIO develops despite the sustained contribution of endogenous leptin to regulate energy balance. Thus, mechanisms opposing leptin must play a crucial role in the development or maintenance of obesity. There is evidence that some of these mechanisms may actually be LEPR dependent, as suggested by the fact that mice overexpressing LEPR in POMC neurons are more susceptible to DIO (Gamber et al., 2012). On the other hand, transgenic mice exhibiting supraphysiological serum leptin levels remain leaner than WT controls on a standard low-fat diet and reach the same BW when made DIO, suggesting that hyperleptinemia alone is not sufficient to reduce endogenous leptin action and cause obesity (Tanaka et al., 2005). Conversely, *ob/ob* mice supplemented with sufficient leptin to prevent obesity while fed a low-fat diet experience similar BW gain compared to WT hyperleptinemic controls once challenged with a HFD, despite remaining responsive to the exogenous administration of leptin (Knight et al., 2010). Assuming the limitations due to the intrinsic differences in leptin action between *ob/ob* mice and WT mice (Bouret et al., 2004), these data suggest that factors other than leptin have a relevant role in the control of BW in conditions of energy surplus. Identifying the factors involved in counteracting the effect of leptin during the development of obesity may provide efficacious targets to prevent BW gain.

The comparable effects of PLA/LA in WT lean and DIO mice suggest that although hyperleptinemic mice may have close to maximal LEPR activity, suppression of steady-state food intake by endogenous leptin remains intact, contributing to the control of energy balance. In our studies, this effect is comparable to that of the lean control mice. This suggestion that our DIO mice have near-maximal endogenous leptin action provides a caveat to the therapeutic application of leptin to treat obesity. The relatively modest effect of leptin to reduce body weight in obese humans may be due to the limited benefit of increasing leptin levels in already hyperleptinemic subjects (Heymsfield et al., 1999). In contrast, use of leptin during BW loss, when leptin levels drop and there is room for further LEPR activation, seems to be a much more effective approach (Clemmensen et al., 2014; Müller et al., 2012; Roth et al., 2008).

Overall, the findings presented here demonstrate comparable endogenous leptin activity in lean and obese hyperleptinemic diet-induced obese mice, despite different sensitivity to exogenously administered leptin. These findings challenge the general assumption of reduced leptin action in obesity, and they should be considered in the development of therapies targeting leptin signaling for the treatment of metabolic disease.

EXPERIMENTAL PROCEDURES

These studies were approved by the Institutional Animal Care and Use Committees at the University of Cincinnati Office in accordance with the US NIH Guide for the Care and Use of Laboratory Animals.

Mice

All mice (C57/Bl6J, Lep$^{ob/ob}$, Lepr$^{db/db}$, and *LoxTbMc4r*) were purchased from The Jackson Laboratory and were acclimated for at least 1 week before the study. Mice were single housed during the study and placed in a 12 hr light/12 hr dark cycle at 22°C with free access to food and water (see also Supplemental Experimental Procedures).

Leptin Antagonists

Native (LA) and 20K-PEGylated (PLA) mouse PLA (mutant D23L/L39A/D40A/F41A) were synthetized and characterized as previously described (Shpilman et al., 2011)

Intraperitoneal Injections

PLA was dissolved in PBS and administered intraperitoneally over a period of 6 days at doses of 1, 3, or 10 mg/kg daily in independent sets of mice. BW and energy intake were monitored daily.

Intracerebroventricular Infusions

Mice received a cannula in the lateral cerebral ventricle connected to a subcutaneous osmotic mini-pump (1007D; Alzet) filled with vehicle (PBS) or LA infused at 8 μg/day for 7 days (see also Supplemental Experimental Procedures).

Gene Expression Analysis

Pomc and *Socs3* gene expression in the arcuate nucleus were analyzed using commercially available gene-specific Taqman probes following manufacturer instructions (see also Supplemental Experimental Procedures) and quantified as described elsewhere (Muller et al., 2002).

Immunoblot

Levels of total STAT3 and pSTAT3 protein in the arcuate nucleus were detected by immunoblot using commercially available antibodies, revealed using chemiluminescense, and quantified using standard imaging techinques (see also Supplemental Experimental Procedures).

Leptin Measurements

Leptin was measured using a commercially available ELISA from Alpco.

Statistical Analyses

Data are presented as mean ± SEM. Analyses were performed using GraphPad Prism, version 6 (GraphPad Software). t tests were used for comparison of two groups, and two-way ANOVA with or without repeated-measures and Sidak multiple comparison tests were used for post hoc comparisons. $p < 0.05$ was considered significant.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures and three figures and can be found with this article online at http://dx.doi.org/10.1016/j.cmet.2015.04.015.

AUTHOR CONTRIBUTIONS

N.O., P.M., B.R., and L.A.N. performed the studies. A.G. provided essential research tools. All the authors analyzed the data. N.O., D.D., and D.P.-T. designed the experiments and wrote the manuscript.

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REFERENCES

Banks, W.A., DiPalma, C.R., and Farrell, C.L. (1999). Impaired transport of leptin across the blood-brain barrier in obesity. Peptides *20*, 1341–1345.

Bjørbaek, C., Elmquist, J.K., Frantz, J.D., Shoelson, S.E., and Flier, J.S. (1998). Identification of SOCS-3 as a potential mediator of central leptin resistance. Mol. Cell *1*, 619–625.

Bouret, S.G., Draper, S.J., and Simerly, R.B. (2004). Trophic action of leptin on hypothalamic neurons that regulate feeding. Science *304*, 108–110.

Caro, J.F., Kolaczynski, J.W., Nyce, M.R., Ohannesian, J.P., Opentanova, I., Goldman, W.H., Lynn, R.B., Zhang, P.L., Sinha, M.K., and Considine, R.V. (1996). Decreased cerebrospinal-fluid/serum leptin ratio in obesity: a possible mechanism for leptin resistance. Lancet *348*, 159–161.

Chapnik, N., Solomon, G., Genzer, Y., Miskin, R., Gertler, A., and Froy, O. (2013). A superactive leptin antagonist alters metabolism and locomotion in high-leptin mice. J. Endocrinol. *217*, 283–290.

Clemmensen, C., Chabenne, J., Finan, B., Sullivan, L., Fischer, K., Küchler, D., Sehrer, L., Ograjsek, T., Hofmann, S.M., Schriever, S.C., et al. (2014). GLP-1/glucagon coagonism restores leptin responsiveness in obese mice chronically maintained on an obesogenic diet. Diabetes *63*, 1422–1427.

Coppari, R., and Bjørbæk, C. (2012). Leptin revisited: its mechanism of action and potential for treating diabetes. Nat. Rev. Drug Discov. *11*, 692–708.

Enriori, P.J., Evans, A.E., Sinnayah, P., Jobst, E.E., Tonelli-Lemos, L., Billes, S.K., Glavas, M.M., Grayson, B.E., Perello, M., Nillni, E.A., et al. (2007). Diet-induced obesity causes severe but reversible leptin resistance in arcuate melanocortin neurons. Cell Metab. *5*, 181–194.

Frederich, R.C., Hamann, A., Anderson, S., Löllmann, B., Lowell, B.B., and Flier, J.S. (1995). Leptin levels reflect body lipid content in mice: evidence for diet-induced resistance to leptin action. Nat. Med. *1*, 1311–1314.

Gabriely, I., Ma, X.H., Yang, X.M., Rossetti, L., and Barzilai, N. (2002). Leptin resistance during aging is independent of fat mass. Diabetes *51*, 1016–1021.

Gamber, K.M., Huo, L., Ha, S., Hairston, J.E., Greeley, S., and Bjørbæk, C. (2012). Over-expression of leptin receptors in hypothalamic POMC neurons increases susceptibility to diet-induced obesity. PLoS ONE *7*, e30485.

Ghamari-Langroudi, M., Srisai, D., and Cone, R.D. (2011). Multinodal regulation of the arcuate/paraventricular nucleus circuit by leptin. Proc. Natl. Acad. Sci. USA *108*, 355–360.

Halaas, J.L., Gajiwala, K.S., Maffei, M., Cohen, S.L., Chait, B.T., Rabinowitz, D., Lallone, R.L., Burley, S.K., and Friedman, J.M. (1995). Weight-reducing effects of the plasma protein encoded by the obese gene. Science *269*, 543–546.

Harris, R.B., Zhou, J., Redmann, S.M., Jr., Smagin, G.N., Smith, S.R., Rodgers, E., and Zachwieja, J.J. (1998). A leptin dose-response study in obese (ob/ob) and lean (+/?) mice. Endocrinology *139*, 8–19.

Heymsfield, S.B., Greenberg, A.S., Fujioka, K., Dixon, R.M., Kushner, R., Hunt, T., Lubina, J.A., Patane, J., Self, B., Hunt, P., and McCamish, M. (1999). Recombinant leptin for weight loss in obese and lean adults: a randomized, controlled, dose-escalation trial. JAMA *282*, 1568–1575.

Huszar, D., Lynch, C.A., Fairchild-Huntress, V., Dunmore, J.H., Fang, Q., Berkemeier, L.R., Gu, W., Kesterson, R.A., Boston, B.A., Cone, R.D., et al. (1997). Targeted disruption of the melanocortin-4 receptor results in obesity in mice. Cell *88*, 131–141.

Ishida-Takahashi, R., Rosario, F., Gong, Y., Kopp, K., Stancheva, Z., Chen, X., Feener, E.P., and Myers, M.G., Jr. (2006). Phosphorylation of Jak2 on Ser(523) inhibits Jak2-dependent leptin receptor signaling. Mol. Cell. Biol. *26*, 4063–4073.

Knight, Z.A., Hannan, K.S., Greenberg, M.L., and Friedman, J.M. (2010). Hyperleptinemia is required for the development of leptin resistance. PLoS ONE *5*, e11376.

Levi, J., Gray, S.L., Speck, M., Huynh, F.K., Babich, S.L., Gibson, W.T., and Kieffer, T.J. (2011). Acute disruption of leptin signaling in vivo leads to increased insulin levels and insulin resistance. Endocrinology *152*, 3385–3395.

Marsh, D.J., Hollopeter, G., Huszar, D., Laufer, R., Yagaloff, K.A., Fisher, S.L., Burn, P., and Palmiter, R.D. (1999). Response of melanocortin-4 receptor-deficient mice to anorectic and orexigenic peptides. Nat. Genet. *21*, 119–122.

Martin, T.L., Alquier, T., Asakura, K., Furukawa, N., Preitner, F., and Kahn, B.B. (2006). Diet-induced obesity alters AMP kinase activity in hypothalamus and skeletal muscle. J. Biol. Chem. *281*, 18933–18941.

Morrison, C.D., White, C.L., Wang, Z., Lee, S.Y., Lawrence, D.S., Cefalu, W.T., Zhang, Z.Y., and Gettys, T.W. (2007). Increased hypothalamic protein tyrosine phosphatase 1B contributes to leptin resistance with age. Endocrinology *148*, 433–440.

Muller, P.Y., Janovjak, H., Miserez, A.R., and Dobbie, Z. (2002). Processing of gene expression data generated by quantitative real-time RT-PCR. Biotechniques *32*, 1372–1374, 1376, 1378–1379.

Müller, T.D., Sullivan, L.M., Habegger, K., Yi, C.X., Kabra, D., Grant, E., Ottaway, N., Krishna, R., Holland, J., Hembree, J., et al. (2012). Restoration of leptin responsiveness in diet-induced obese mice using an optimized leptin analog in combination with exendin-4 or FGF21. J. Pept. Sci. *18*, 383–393.

Münzberg, H., Huo, L., Nillni, E.A., Hollenberg, A.N., and Bjørbaek, C. (2003). Role of signal transducer and activator of transcription 3 in regulation of hypothalamic proopiomelanocortin gene expression by leptin. Endocrinology *144*, 2121–2131.

Münzberg, H., Flier, J.S., and Bjørbaek, C. (2004). Region-specific leptin resistance within the hypothalamus of diet-induced obese mice. Endocrinology *145*, 4880–4889.

Myers, M.G., Cowley, M.A., and Münzberg, H. (2008). Mechanisms of leptin action and leptin resistance. Annu. Rev. Physiol. *70*, 537–556.

Myers, M.G., Jr., Heymsfield, S.B., Haft, C., Kahn, B.B., Laughlin, M., Leibel, R.L., Tschöp, M.H., and Yanovski, J.A. (2012). Challenges and opportunities of defining clinical leptin resistance. Cell Metab. *15*, 150–156.

Newton, A.J., Hess, S., Paeger, L., Vogt, M.C., Fleming Lascano, J., Nillni, E.A., Brüning, J.C., Kloppenburg, P., and Xu, A.W. (2013). AgRP innervation onto POMC neurons increases with age and is accelerated with chronic high-fat feeding in male mice. Endocrinology *154*, 172–183.

Roth, J.D., Roland, B.L., Cole, R.L., Trevaskis, J.L., Weyer, C., Koda, J.E., Anderson, C.M., Parkes, D.G., and Baron, A.D. (2008). Leptin responsiveness restored by amylin agonism in diet-induced obesity: evidence from nonclinical and clinical studies. Proc. Natl. Acad. Sci. USA *105*, 7257–7262.

Scarpace, P.J., Matheny, M., Moore, R.L., and Tümer, N. (2000). Impaired leptin responsiveness in aged rats. Diabetes *49*, 431–435.

Seeley, R.J., Yagaloff, K.A., Fisher, S.L., Burn, P., Thiele, T.E., van Dijk, G., Baskin, D.G., and Schwartz, M.W. (1997). Melanocortin receptors in leptin effects. Nature *390*, 349.

Shpilman, M., Niv-Spector, L., Katz, M., Varol, C., Solomon, G., Ayalon-Soffer, M., Boder, E., Halpern, Z., Elinav, E., and Gertler, A. (2011). Development and characterization of high affinity leptins and leptin antagonists. J. Biol. Chem. *286*, 4429–4442.

Solomon, G., Atkins, A., Shahar, R., Gertler, A., and Monsonego-Ornan, E. (2014). Effect of peripherally administered leptin antagonist on whole body metabolism and bone microarchitecture and biomechanical properties in the mouse. Am. J. Physiol. Endocrinol. Metab. *306*, E14–E27.

Tanaka, T., Hidaka, S., Masuzaki, H., Yasue, S., Minokoshi, Y., Ebihara, K., Chusho, H., Ogawa, Y., Toyoda, T., Sato, K., et al. (2005). Skeletal muscle AMP-activated protein kinase phosphorylation parallels metabolic phenotype in leptin transgenic mice under dietary modification. Diabetes *54*, 2365–2374.

Tümer, N., Erdös, B., Matheny, M., Cudykier, I., and Scarpace, P.J. (2007). Leptin antagonist reverses hypertension caused by leptin overexpression, but fails to normalize obesity-related hypertension. J. Hypertens. *25*, 2471–2478.

Zhang, Y., Proenca, R., Maffei, M., Barone, M., Leopold, L., and Friedman, J.M. (1994). Positional cloning of the mouse obese gene and its human homologue. Nature *372*, 425–432.

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Supplemental Information

Diet-Induced Obese Mice Retain Endogenous Leptin Action

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Supplemental data.

Figure S1

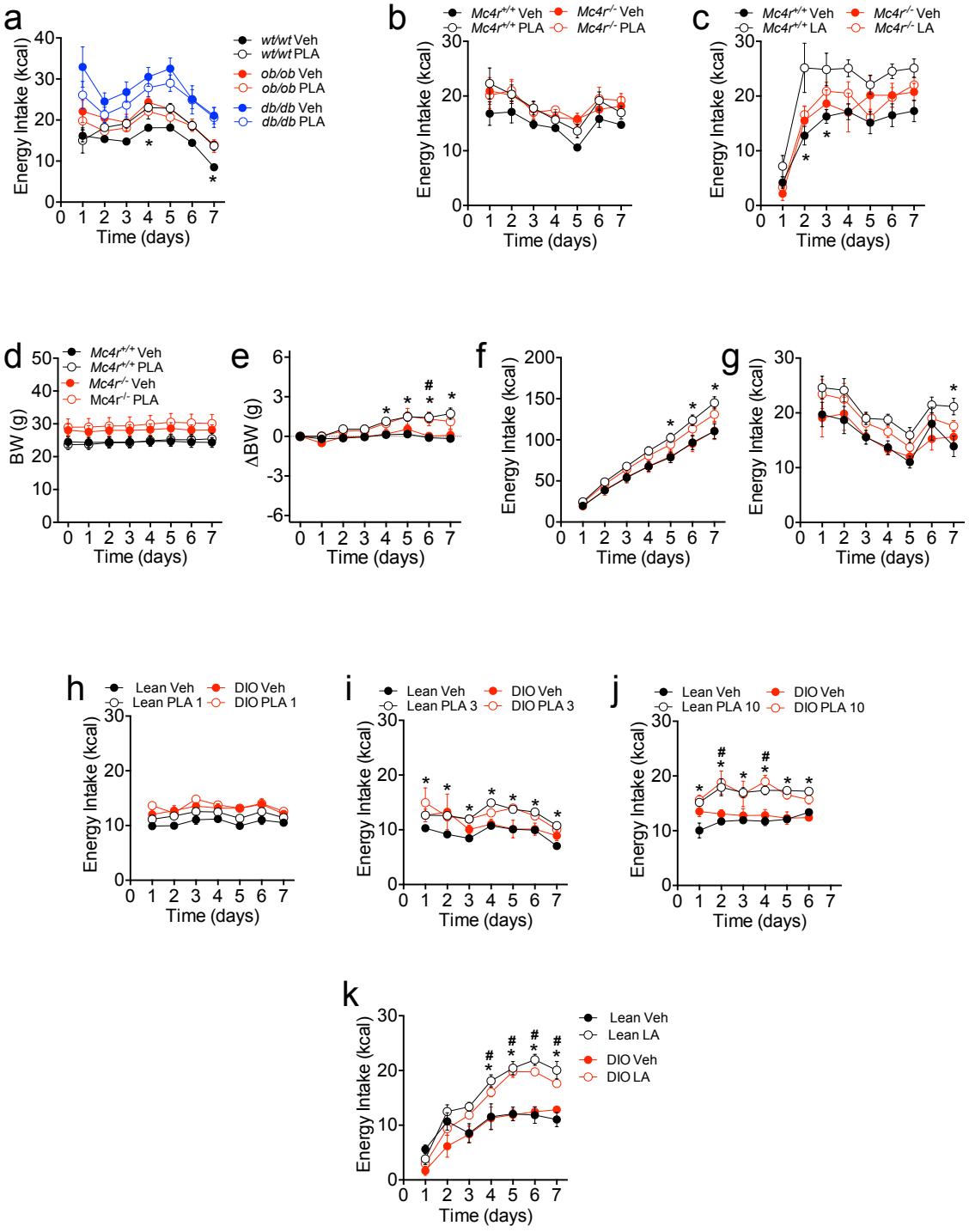

Figure S1 (related to Figures 1-3): (a) Effect on daily energy intake of peripheral administration of 20K-PEG leptin antagonist (PLA, 3 mg/kg, ip, once daily) in chow fed *db/db, ob/ob* or lean *wildtype* control mice.

(b,c) Effect on daily energy intake of peripheral administration of 20K-PEG leptin antagonist (PLA, 3 nmol/kg, ip, once daily, b) or Icv infusion of leptin antagonist (LA, 8ug/day, icv, c) in chow fed obese *Mc4r-/-* or *wildtype* littermate control male mice.

(d-g) Effect on daily energy intake of peripheral administration of 20K-PEG leptin antagonist (PLA, 3 nmol/kg, ip, once daily) in chow fed lean (5-14 week old) *Mc4r-/-* or *wildtype* littermate control male mice.

(h-j) Effect on daily energy intake of peripheral administration of 20K-PEG leptin antagonist (PLA, 1 (h), 3 (i) or 10 (j) nmol/kg, ip, once daily) in lean and DIO mice.

(k) Effect on daily energy intake of Icv infusion of a leptin antagonist (LA, 8 ug/day) in lean and DIO mice.

(a) * $P<0.05$ *wt/wt* Veh vs. *wt/wt* PLA; (b, c) *$P<0.05$ *Mc4r*+/+ Veh vs. *Mc4r*+/+ PLA.

(d-g) *$P<0.05$ *Mc4r*+/+ Veh vs. *Mc4r*+/+ PLA; # $P<0.05$ *Mc4r-/-* Veh vs. *Mc4r-/-* PLA;

(f), $P<0.05$ treatment x time, *Mc4r-/-* Veh vs. *Mc4r-/-* PLA.

(h-k) *$P<0.05$ Lean Veh vs. Lean PLA or LA; # $P<0.05$ DIO Veh vs. DIO PLA or LA.

Data are presented as mean ± SEM. n=8-5; 2-way RM ANOVA followed by Sidak test.

Figure S2.

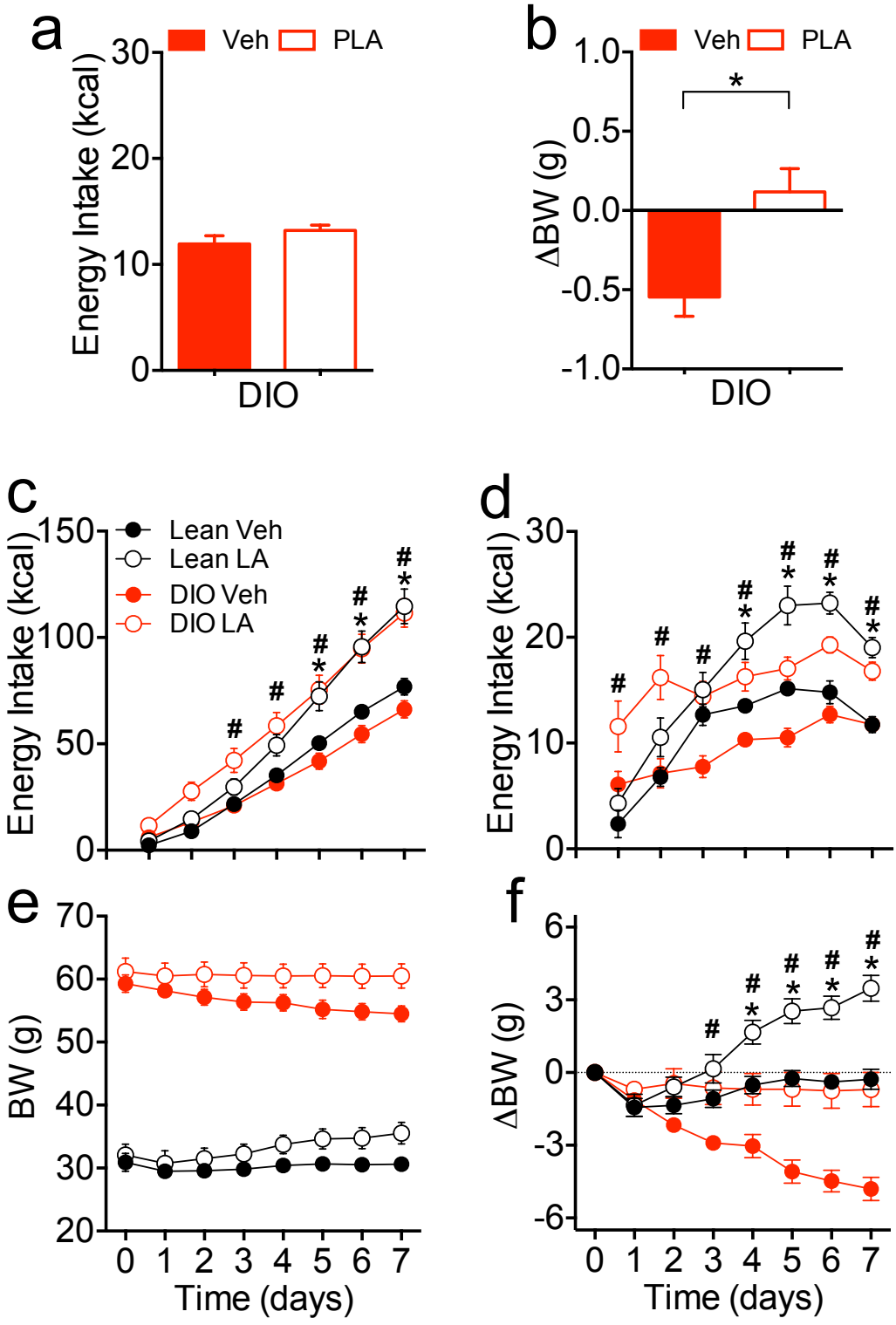
a
Veh
PLA
Energy Intake (kcal)
30
20
10
0
DIO
b
Veh
PLA
*
1.0
0.5
0.0
-0.5
-1.0
ΔBW (g)
DIO
c
Lean Veh
Lean LA
DIO Veh
DIO LA
Energy Intake (kcal)
150
100
50
0
d
Energy Intake (kcal)
30
20
10
0
e
BW (g)
70
60
50
40
30
20
0 1 2 3 4 5 6 7
Time (days)
f
ΔBW (g)
6
3
0
-3
-6
0 1 2 3 4 5 6 7
Time (days)

Figure S2 (related to Figure 4): (a,b) Effect on energy intake (a) and body weight change (b) of a single peripheral injection of 20K-PEG leptin antagonist (PLA, 3 mg/kg, ip, -12h) in DIO mice; (c-f) Effect of 7-day icv infusion of a leptin antagonist (LA, 8 ug/day) in lean and DIO mice on energy intake (c and d, cumulative and daily values, respectively), total BW (e) or BW change (f). Levels of pSTAT3 levels in the ARC of these mice are shown in Figure S3 and represented in Figure 4e,f.

(b) * $P<0.05$. (c-f) *$P<0.05$ Lean Veh vs. Lean LA; #$P<0.05$ DIO Veh vs. DIO LA. (a,b) n=12-13, t-Student test; (c-f). Data are presented as mean ± SEM. n=6, 2-way RM ANOVA, followed by Sidak test.

Figure S3

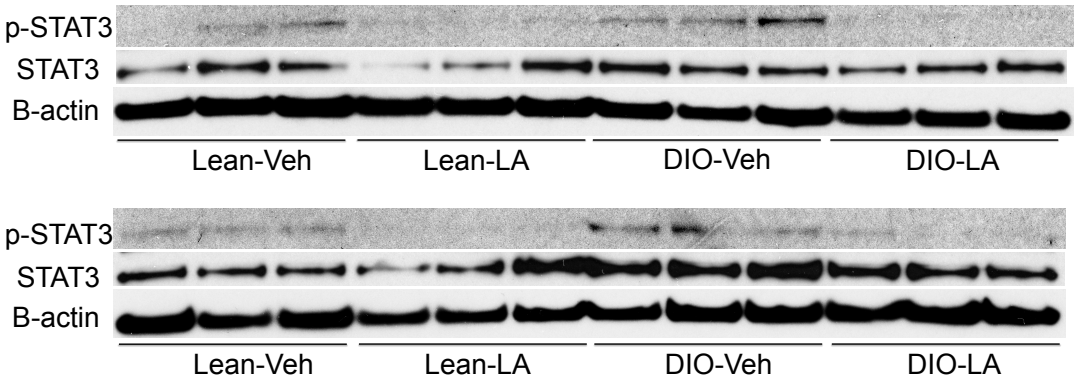
p-STAT3
STAT3
B-actin
Lean-Veh
Lean-LA
DIO-Veh
DIO-LA
p-STAT3
STAT3
B-actin
Lean-Veh
Lean-LA
DIO-Veh
DIO-LA

Figure S3 (related to Figure 4): Inmunoblots showing p-STAT3 (first and fourth lane), total STAT3 (second and fifth lane) and beta actin (third and sixth lane) levels in the ARC of lean and DIO mice treated icv with vehicle or LA (8ug/day, 7-d). The densitometric analysis of the bands is depicted in Figure 4e, f. The impact of the treatment on energy intake and body weight is depicted in Figure S2c-f.

Supplemental Experimental Procedures.

Mice: All mice were purchased from Jackson Laboratories (Bar Harbor, ME) and were acclimated for at least one week before the study. Mice were single-housed during the study and placed in a 12-h light, 12-h dark cycle at 22 °C with free access to food and water. (See extended experimental procedures)

C57/B6 male mice were obtained from Jackson Laboratories (Bar Harbor, ME) at 8-weeks of age and maintained on a standard chow 17% fat (Teklad; Harlan) or a high-sucrose diet with 58% kcal from fat (Research Diets #D12331, New Brunswick, NJ), for 8 months. *LoxTbMc4r* (KO) mice were ordered from Jackson Laboratory (Stock #006414), bred in-house as heterozygotes to obtain homozygous mutants and *wildtype* littermates and maintained on standard chow. Leptin receptor deficient (*db/db)* (Stock #000642), leptin deficient *(ob/ob)* (Stock #000632) and *wildtype* controls of *ob/ob* mice were ordered at 10 weeks of age from Jackson Laboratory and were maintained on standard chow.

Leptin antagonists: Native (LA) and 20k-pegylated (PLA) mouse PLA (mutant D23L/L39A/D40A/F41A) were synthetized and characterized as previously described The D23L mutation in the antagonist increases the affinity of the antagonists toward LEPR by 60-fold and has a 10 to 30-fold higher in vivo weight-gain effect compared to MLA (Shpilman et al., 2011), and pegylation prolongs the half-life in circulation, which greatly improves its efficacy when administered peripherally (Chapnik et al., 2013; Shpilman et al., 2011; Solomon et al., 2014)

Intracerebroventricular Infusions: Mice were anesthetized with 2% isoflurane in oxygen. Stainless steel cannulas were stereotaxically placed in the lateral cerebral ventricle using the following coordinates: 0.7 mm posterior to bregma, 1.2 mm lateral to the mid-sagittal suture, and 2.5 mm ventrally from the surface of the brain. The cannula was connected to an osmotic minipump (1007D; Alzet, Cupertino, CA) filled with vehicle (PBS) or LA placed subcutaneously through a polyvinyl tube. The cannulas were secured to the skull and the skin was closed using Vetbond (3M. St. Paul, MN). The animals received a single s.c. dose of 5 mg/kg of meloxiocam (Metacam, Boehringer Ingelheim, Ingelheim, Germany).

Gene expression analysis: The arcuate nucleus was dissected from the frozen hypothalamic block and the RNA was extracted (RNAqueous-Micro kit). An aliquot of RNA was run in 1% agarose gel to confirm the integrity. cDNA was synthetized with SuperScript® III First-Strand Synthesis kit (Invitrogen, Life Technologies) after DNAse I treatment (Invitrogen, Life Technologies) and qPCR was performed using commercially available gene-specific Taqman® probes following manufacturer instructions (Invitrogen, Life Technologies). Water-blank samples from the cDNA synthesis were included in the qPCR reaction. Beta actin was used as housekeeping gene and the relative quantification was performed using the Q-gen software (Muller et al., 2002)

Inmunoblot: The arcuate nucleus was dissected immediately after euthanasia and frozen in liquid nitrogen. The tissue was homogenized in lysis buffer containing Halt protease and phosphatase inhibitor cocktail (Thermo Fisher Scientific Inc., Rockford, IL USA), 0.5mM PMSF and 0.1mM benzamidine (Sigma-Aldrich, St. Louis, MO, USA) using a Tissuelyser (Quiagen). The samples were rocked at 4 C for 30 min, passed through a 28-g

syringe neddle, centrifuged for 15 min at 4 C and 23,000 × g, and the supernatants collected in a fresh tube. Protein concentrations were measured using a Pierce BCA method protein assay kit (Thermo Fisher Scientific Inc). 45ug separated by electrophoresis in denaturing conditions using 10% Bis-Tris gels pre-cast polyacrylamide gels (Invitrogen, Life Technologies) and the proteins were transferred overnight to polyvinylidene difluoride (PVDF) membranes previously incubated in methanol for 3 minutes. The membranes were cut, blocked in 5% nonfat dried milk (20 mm Tris, pH 7.6; 0.9% NaCl; 0.1% Tween 20) and independently incubated overnight at 4C with p-STAT3 (1:1000, Cell Signaling Technology, MA) or beta actin antibody (1:5000, Cell Signaling). Membranes were then washed and incubated with secondary antibodies (antirabbit-horseradish peroxidase coupled, 1:10,000; Cell Signaling), washed and developed by enhanced chemiluminescence (ECL2 Plus, Thermo Fisher Scientific Inc) and x-ray films (Denville Scientific). The membrane containing p-STAT3 was then washed three times, blocked and incubated overnight at 4C with an antibody against total STAT3 (Cell Signaling, 1:2000) and revealed as described above. Films were scanned and densitometry was assessed using ImageJ 1.48v (http://imagej.nih.gov/ij).