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Insufficiency of Janus Kinase 2–Autonomous Leptin Receptor Signals for Most Physiologic Leptin Actions

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OBJECTIVE—Leptin acts via its receptor (LepRb) to signal the status of body energy stores. Leptin binding to LepRb initiates signaling by activating the associated Janus kinase 2 (Jak2) tyrosine kinase, which promotes the phosphorylation of tyrosine residues on the intracellular tail of LepRb. Two previously examined LepRb phosphorylation sites mediate several, but not all, aspects of leptin action, leading us to hypothesize that Jak2 signaling might contribute to leptin action independently of LepRb phosphorylation sites. We therefore determined the potential role in leptin action for signals that are activated by Jak2 independently of LepRb phosphorylation (Jak2-autonomous signals).

RESEARCH DESIGN AND METHODS—We inserted sequences encoding a truncated LepRb mutant (LepRbΔNec, which activates Jak2 normally, but is devoid of other LepRb intracellular sequences) into the mouse Lepr locus. We examined the leptin-regulated physiology of the resulting ΔΔ mice relative to LepRb-deficient db/db animals.

RESULTS—The ΔΔ animals were similar to db/db animals in terms of energy homeostasis, neuroendocrine and immune function, and regulation of the hypothalamic arcuate nucleus, but demonstrated modest improvements in glucose homeostasis.

CONCLUSIONS—The ability of Jak2-autonomous LepRb signals to modulate glucose homeostasis in ΔΔ animals suggests a role for these signals in leptin action. Because Jak2-autonomous LepRb signals fail to mediate most leptin action, however, signals from other LepRb intracellular sequences predominate. Diabetes 59:782–790, 2010

A dipose tissue produces the hormone, leptin, in proportion to fat stores to communicate the status of long-term energy reserves to the brain and other organ systems (1–4). In addition to moderating food intake, adequate leptin levels permit the expenditure of energy on myriad processes including reproduction, growth, and immune responses, as well as regulating nutrient partitioning (4–6). Conversely, lack of leptin signaling due to null mutations of leptin (e.g., Lepob/ob mice) or the leptin receptor (LepR) (e.g., LepRb/ob/db mice) results in increased food intake in combination with reduced energy expenditure (and thus obesity), neuroendocrine dysfunction (including hypothyroidism, decreased growth, infertility), decreased immune function, and hyperglycemia and insulin insensitivity (1,7–9). Many of the effects of leptin are attributable to effects in the central nervous system, particularly in the hypothalamus, but leptin also appears to act directly on some other tissues (2,3).

Alternative splicing generates several integral-membrane LepR isoforms that possess identical extracellular, transmembrane, and membrane-proximal intracellular domains. LepR intracellular domains diverge beyond the first 29 intracellular amino acids, however, with the so-called “short” isoforms (e.g., LepRa) containing an additional 3–10 amino acids, and the single “long” isoforms (LepRb) containing a 300–amino acid intracellular tail (10). Like other type I cytokine receptors (11), LepRb (which is required for physiologic leptin action) contains no intrinsic enzymatic activity, but associates with and activates the Janus kinase 2 (Jak2) tyrosine kinase to mediate leptin signaling. The intracellular domain of LepRb possesses membrane-proximal Box1 and Box2 motifs, both of which are required for association with and regulation of Jak2; although LepRa and other short LepRs contain Box1, they lack Box2 and thus fail to bind and activate Jak2 under physiologic conditions (12).

Leptin stimulation promotes the autophosphorylation and activation of LepRb-associated Jak2, which phosphorylates three LepRb tyrosine residues (Tyr985, Tyr1077, and Tyr1138). Each LepRb tyrosine phosphorylation site recruits specific Src homology 2 (SH2) domain–containing effector proteins: Tyr985 recruits Src homology phosphatase-2 (SHP-2) and suppressor of cytokine signaling 3 and attenuates LepRb signaling, but does not appear to play other roles in leptin action in vivo (13–15). Tyr1077 recruits the latent transcription factor, signal transducer, and activator of transcription 5 (STAT5), and Tyr1138 recruits STAT3 (16–18). Mice in which LepRbΔ1138 (mutant for Tyr1138 and thus specifically unable to recruit STAT3) replaces endogenous LepRb exhibit hyperphagic obesity, with decreased energy expenditure, but increased growth, protection from diabetes, and preservation of several aspects of hypothalamic physiology (19–21). These results thus suggest roles for Tyr1077 and/or Jak2-dependent signals that are independent of LepRb tyrosine phosphorylation (“Jak2-autonomous signals”) in mediating Tyr985/Tyr1138-independent leptin actions. Although others have examined the effect of mutating all three LepRb tyrosine phosphorylation sites in mice (22), revealing potential tyrosine phosphorylation–independent roles for LepRb in leptin action, that study did not examine several aspects of leptin action and could not distinguish potential effects of...
nonphosphorylated LepRb motifs from effects due to LepRb/Jak2 interactions specifically.

**RESEARCH DESIGN AND METHODS**

**Cell culture studies.** The plasmids pCDNA3LepRb<sup>Δ65</sup> and pCDNA3LepRa were generated by mutagenesis of pCDNA3LepRb (23) using the QuickChange kit (Stratagene). The absence of adventitious mutations was confirmed by DNA sequencing for all plasmids. Cell culture, transfection, lysis, and immunoblotting were conducted as reported previously using a Jak2(pY1007/8) from Cell Signaling Technology and a Jak2 from our own laboratory (24). Leptin was the generous gift of Amylin Pharmaceuticals (La Jolla, CA).

**Mouse model generation.** The targeting vector encoding LepRb<sup>Δ65</sup> was generated by inserting a Stop codon (QuikChange kit) after the 65th intracellular amino acid of LepRb in the 5′ targeting arm in the pBluescript plasmid; this modified 5′-arm was subsequently subcloned into the previously described pPNT-derived targeting vector that contained the 3′ arm (19,25,26). The resulting construct was linearized and transfected into murine embryonic stem (ES) cells with selection of clones by the University of Michigan Transgenic Animal Model Facility. Correctly targeted clones were identified and confirmed with real-time PCR and Southern blotting as performed previously (15,21,26) and were injected into embryos for the generation of chimeras and the establishment of germ-line Lepr<sup>Δ55/-</sup> (Δ−/−) animals. Δ−/− animals were intercrossed to generate +/+ and ΔΔ mice for the determination of hypothalamic Lepr expression or were backcrossed onto the C57BL/6J background (The Jackson Laboratory) for six generations prior to intercrossing to generate +/+ and ΔΔ animals for the collection of other data. 

**Experimental animals.** C57BL/6J wildtype, Lep<sup>Δ55</sup>−/−, and Lep<sup>Δ55</sup>−/+ mice were purchased from The Jackson Laboratory. All other animals and progeny from these purchased breeders were housed and bred in our colony and were cared for and used according to guidelines approved by the University of Michigan Committee on the Care and Use of Animals. After weaning, all mice were maintained on 5011 LabDiet chow. Mice were given ad libitum access to food and water unless otherwise noted. For body weight, food intake, glucose monitoring, and estrous monitoring, animals were weaned at 4 weeks and housed individually. Body weight and food intake were recorded weekly from 4 to 8 weeks. Whole venous blood from the tail vein was used to determine blood glucose (Ascensia Elite glucometer) and to obtain serum, which was frozen for later hormone measurement. A terminal bleed was also collected at the time of killing. Commercial ELISA kits were used to determine insulin (Crystal Chem), leptin (Crystal Chem), and C-peptide (Millipore) concentrations.

In females, vaginal lavage was used to assess estrous cycling daily from 4 to 8 weeks. Animals intended for glucose tolerance tests, insulin tolerance tests, and body composition were weaned at 4 weeks and group housed. Body composition was determined using an NMR Minispec LF90II scanner (Bruker Optics) at the University of Michigan Animal Phenotyping Core.

**Analysis of hypothalamic RNA.** Hypothalami were isolated from ad libitum-fed mice and snap-frozen. Total RNA was isolated using Trizol RNA reagent (Invitrogen) and converted to cDNA using SuperScript reverse transcriptase (Invitrogen). For comparison of relative LepRb expression, total hypothalamic cDNA was subjected to PCR with LepRb-specific primers and subjected to gel electrophoresis (21). For determination of relative neuropeptide expression, cDNA was subjected to PCR with LepRb-specific primers and subjected to gel electrophoresis (21). For determination of relative neuropeptide expression, cDNA was subjected to PCR with LepRb-specific primers and subjected to gel electrophoresis (21).

**Immunologic cell analysis.** For counting total splenocytes and splenic T-cells, splenic T-cells were magnetically separated from the spleen by autoMACS (Miltenyi Biotech, Bergisch Gladbach, Germany) as previously described and counted by flow cytometry (27). For proliferation assays, T-cells were separated using CD90 microbeads, and 2 × 10⁶ of these were incubated with 2 × 10⁶ B6 bone marrow–derived dendritic cells for 48, 72, and 96 h. Cells were stimulated with soluble anti-CD3ε (1 mg/ml). Incorporation of ³H-thymidine (1 µCi/well) by proliferating cells during the last 12 h of culture was measured.

**Immunohistochemical analysis of hypothalamic brain sections.** +/+, db/+,-, and ΔΔ were intercrossed with heterozygous Agrp<sup>LacZ</sup> mice expressing LacZ from the Agrp locus (28,29) before reccrossing to the parent Lepr strain to generate all animals. For immunohistochemical analysis, ad libitum–fed animals remained with food in the cage until the time of death. Perfusion and immunohistochemistry were performed as described (30).

**RESULTS**

**LepRb<sup>Δ65</sup> and gene targeting to generate LepRb<sup>Δ65</sup>.** To examine physiologic signals generated by LepRb-associated Jak2 in the absence of LepRb tyrosine phosphorylation sites and other LepRb motifs (Jak2-autonomous signals), we used a COOH-terminal truncation mutant of LepRb (LepRb<sup>Δ65</sup>) that contains all motifs required for Jak2 association and regulation, but which is devoid of other intracellular LepRb sequences (12). Because we previously demonstrated the function of this mutant intracellular domain in the context of an erythropoietin receptor (extracellular domain)/LepRb (intracellular domain) chimera (12), we initially examined signaling by the truncated intracellular domain within the context of LepRb<sup>Δ65</sup> in transfected 293 cells (Fig. 1A). Leptin stimulation promoted the phosphorylation of Jak2 on the activating Tyr<sub>1007/1008</sub> sites in LepRb<sup>Δ65</sup> and LepRb-expressing cells but not in LepRa-expressing or control cells (Fig. 1A), confirming that LepRb and LepRb<sup>Δ65</sup>, but not LepRa, contain the necessary sequences to mediate Jak2 activation in response to leptin.

To understand the potential roles for Jak2-autonomous LepRb signals in leptin action, we used homologous recombination to replace the genomic Lepr with LepRb<sup>Δ65</sup> (henceforth referred to as the Δ allele, encoding LepRb<sup>Δ65</sup> in mouse ES cells (Fig. 1B). Correctly targeted ES cell clones were confirmed by Southern blotting (Fig. 1C). This strategy mediates LepRb<sup>Δ65</sup> expression from the native Lepr locus, ensuring correct patterns and levels of LepRb<sup>Δ65</sup> expression, as previously for other homologously targeted LepRb alleles (15,21,26). Indeed, RT-PCR analysis of hypothalamic mRNA confirmed similar Lepr mRNA expression in homozygous ΔΔ animals and wild-type animals (Fig. 1D). Prior to subsequent study, we backcrossed heterozygous Δ−/− animals to C57BL/6J mice for six generations to facilitate direct comparison with LepRb<sup>Δ65</sup> (db/db) animals on this background.

**Energy homeostasis in ΔΔ mice.** Because our previous analysis suggested some role for Tyr<sub>985</sub>/Tyr<sub>1138</sub>-independent LepRb signals in regulating energy balance, we initially examined parameters of energy homeostasis in ΔΔ compared with db/db animals (15,19,21). We weaned and singly housed ΔΔ, db/db, and control mice from 4 to 8 weeks of age for the longitudinal determination of body weight and food intake (Fig. 2A–D). Compared with age- and sex-matched db/db animals, ΔΔ mice displayed similar body weights and food intake over the study period. Furthermore, age- and sex-matched ΔΔ and db/db mice displayed similar proportions of fat and lean mass (Table 1), revealing that ΔΔ and db/db mice are similarly obese. Core body temperature in ΔΔ and db/db animals was also similarly reduced compared with control animals (Table 1). Thus, LepRb<sup>Δ65</sup> fails to alter major parameters of energy homeostasis compared with entirely LepRb-deficient db/db mice, suggesting that Jak2-autonomous LepRb signals are not sufficient to modulate energy balance in mice.

**Linear growth and reproductive function in ΔΔ mice.** In addition to modulating metabolic energy expenditure, leptin action permits the use of resources on energy-intensive neuroendocrine processes, such as growth and reproduction. Whereas db/db and ob/ob animals that are devoid of leptin action thus display decreased linear growth and infertility, animals lacking Tyr<sub>985</sub> or Tyr<sub>1138</sub> of LepRb display normal or enhanced linear growth and preserved reproductive function, suggesting a role for other LepRb signals in mediating these leptin actions (15,19,21). Similar to db/db mice, ΔΔ males displayed decreased snout-anus length and femur length relative to control animals (Table 1), however, suggesting the inabil-
ROLE OF Jak2 IN LEPTIN ACTION

FIG. 1. Generation of mice expressing LepRb<sup>Δ65</sup>. A: HEK293 cells were transfected with plasmids encoding the indicated LepR isoforms, made quiescent overnight, incubated in the absence (−) or presence (+) of leptin (625 ng/ml) for 15 min before lysis, and immunoprecipitated with α-Jak2 (24). Immunoprecipitated proteins were resolved by SDS-PAGE, transferred to nitrocellulose, and immunoblotted with the indicated antibodies. The figures shown are typical of multiple independent experiments. B: Diagram of gene-targeting strategy to replace wild-type exon 18b with that encoding the COOH-terminally truncated LepRb<sup>Δ65</sup>. C: Southern blots of control (wild-type) and correctly targeted (D/+, C1, C2) Lepr<sup>Δ65</sup> ES lines, using a Lepr-specific probe. M indicates marker lane. D: Image of gel electrophoresis of Lepr-specific RT-PCR products from hypothalamic mRNA of five wild-type and five Δ/Δ animals.

ity of Jak2-autonomous LepRb signals to mediate linear growth in the absence of other LepRb signals.

To determine the potential role for Jak2-autonomous LepRb signals in the regulation of reproductive function, we monitored estrous cycling from 4 to 8 weeks of age in female mice, along with their ability to deliver pups after housing with wild-type males. In addition to examining Δ/Δ, db/db, and wild-type females in these assays, we included mice homozygous for Lep<sup>tm1mgmj</sup> (a.k.a., Lep<sup>Δ1138</sup>) or s/s mice; mutant for Tyr<sup>1138</sup>→STAT3 signaling) (21) as a positive control for our ability to detect residual reproductive function in obese mice with altered leptin action (Table 2). Whereas essentially all wild-type females and approximately half of the s/s females displayed vaginal estrus when housed in the absence of males and delivered pups after cohabitation with male mice, Δ/Δ females, like db/db animals, failed to undergo estrus or deliver pups. Gross examination also revealed the reproductive organs of Δ/Δ females were atrophic and similar to those of db/db females (data not shown). Thus, Jak2-autonomous LepRb signals are not sufficient to mediate leptin action on the reproductive axis.

Regulation of the hypothalamic ARC in Δ/Δ animals.

A number of aspects of leptin action in the hypothalamus are beginning to be unraveled, including the role of leptin in regulating arcuate nucleus (ARC) LepRb/proopiomelanocortin (POMC)-expressing neurons and their opposing LepRb/agouti-related protein/neuropeptide Y (AgRP/NPY)-expressing neurons (2,3,31,32). Leptin promotes anorectic POMC expression, while inhibiting the expression of orexigenic AgRP and NPY and attenuating the activity of AgRP/NPY neurons. Although LepRb Tyr<sup>1138</sup>→STAT3 signaling is required to promote Pomp mRNA expression, signals independent of Tyr<sup>685</sup> and Tyr<sup>1138</sup> contribute to the suppression of Agrp and Npy mRNA expression, and to the inhibition of AgRP neuron activity (15,21,29). To determine the potential role for Jak2-autonomous LepRb signals in the regulation of these ARC neurons, we examined the mRNA expression of Pomp, Npy, and Agrp in the hypothalamus and examined c-fos immunoreactivity (c-fos-IR) as a surrogate for activity in AgRP neurons (29) of male Δ/Δ, db/db, and wild-type mice (Fig. 3). As expected based on the known role for Tyr<sup>1138</sup> in regulating Pomp, Δ/Δ and db/db mice exhibited significantly diminished Pomp mRNA expression compared with wild-type controls (Fig. 3A); Pomp levels in Δ/Δ mice were lower even than those in db/db mice. We found similarly elevated Npy and Agrp mRNA expression in Δ/Δ and db/db mice compared with wild-type mice (Fig. 3B and C).

To analyze c-fos-IR in AgRP neurons, we generated +/+Δ, Δ/Δ, and db/db animals heterozygous for Agrp<sup>LacZ</sup>, in which β-galactosidase (β-gal) is expressed from the Agrp locus, facilitating the detection of AgRP-expressing neurons by β-gal immunofluorescence (29). Although fed wild-type animals displayed c-fos-IR in few AgRP neurons, a similarly large percentage of AgRP neurons in Δ/Δ and db/db animals contained c-fos-IR, suggesting their activity (Fig. 3D and E). Thus, Jak2-autonomous LepRb signals are not sufficient to mediate either the normal regulation of ARC neuropeptide gene expression or the suppression of c-fos-IR activity in AgRP neurons.

Regulation of T-cell function by LepRb signals. Leptin signals the status of energy stores to the immune system, as well as to the brain systems that control energy balance and neuroendocrine function. Leptin deficiency results in thymic hypoplasia, reduced T-cell function, and consequent immune suppression (6,33). Although we previously...
examined thymocyte numbers in young s/s mice deficient for LepRb Tyr1138 signaling, suggesting improved immune function in s/s compared with db/db mice (23), many other parameters of immune function in these and other models of altered LepRb signaling remain poorly understood. To better understand the signaling mechanisms by which LepRb modulates the immune system, we thus determined the numbers of total and CD4/H11001 splenocytes, as well as the ex vivo proliferative capacity of splenic CD4/H11001 cells from a panel of mouse models of altered LepRb signaling. In addition to examining wild-type, ob/ob, ΔΔ, and s/s animals, we also studied mice homozygous for LepfH11001mo2mgmj (a.k.a., LepfH11001m05 or /l) mutant for LepRb Tyr985 (15) (Fig. 4). Note that ob/ob animals were used as the control for the absence of leptin action in this study, as sufficient numbers of age-matched db/db animals were not available at the time of assay. In addition to revealing the expected decrease in total and CD4/H11001 splenocytes and their proliferation in ob/ob animals relative to wild-type controls, we found decreases in these parameters in s/s animals, and normal parameters of immune function in s/s animals. Interestingly, although l/l animals exhibit increased sensitivity to the anorexic action of leptin (15), these parameters of immune function actually trended down (albeit not significantly) compared to wild-type controls.

### Table 1
Phenotypic data for mice expressing mutant LepRb

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Wild type</th>
<th>db/db</th>
<th>ΔΔ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat content (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>6.0 ± 0.7 (10)</td>
<td>47.0 ± 1.1* (8)</td>
<td>47.8 ± 0.9* (8)</td>
</tr>
<tr>
<td>Female</td>
<td>6.4 ± 0.5 (8)</td>
<td>51.0 ± 0.9* (8)</td>
<td>54.1 ± 0.7* (11)</td>
</tr>
<tr>
<td>Lean content (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>80.0 ± 0.4 (10)</td>
<td>43.7 ± 1.1* (8)</td>
<td>42.6 ± 0.8* (8)</td>
</tr>
<tr>
<td>Female</td>
<td>76.0 ± 3.0 (8)</td>
<td>39.5 ± 0.7* (8)</td>
<td>37.5 ± 0.6* (10)</td>
</tr>
<tr>
<td>Body temperature (°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>34.6 ± 0.2 (10)</td>
<td>33.0 ± 0.2* (9)</td>
<td>33.4 ± 0.2* (8)</td>
</tr>
<tr>
<td>Female</td>
<td>34.4 ± 0.3 (8)</td>
<td>33.8 ± 0.2 (9)</td>
<td>33.5 ± 0.3 (12)</td>
</tr>
<tr>
<td>Snout-anus length (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>88.5 ± 0.8 (9)</td>
<td>82.6 ± 2.7* (8)</td>
<td>83.0 ± 1.0* (9)</td>
</tr>
<tr>
<td>Femur length (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>13.9 ± 0.1 (9)</td>
<td>11.8 ± 0.1* (8)</td>
<td>12.0 ± 0.1* (9)</td>
</tr>
<tr>
<td>Femur mass (mg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>42.4 ± 0.6 (9)</td>
<td>34.8 ± 0.8* (8)</td>
<td>35.3 ± 0.9* (9)</td>
</tr>
</tbody>
</table>

Fat and lean content were determined at 10 weeks and are expressed as a percentage of body weight. Body temperature was determined at 11 weeks. Snout-anus length, femur length, and femur weight were determined at 9 weeks. Data are means ± SE; *P < 0.05 compared with wild type by Student unpaired, two-tailed t test. Sample size noted in parentheses.
significantly) compared with wild-type animals. Thus, these data suggest that although Tyr985 and Tyr1138 are not required for the promotion of splenic T-cell function by leptin, Jak2-autonomous LepRb signals are not sufficient to mediate these aspects of leptin action.

**Glucose homeostasis in ΔΔ mice.** Given the role for leptin in modulating long-term glucose homeostasis (2,20,34), we examined glycemic control in ΔΔ mice. Interestingly, we found that at 4 weeks of age, the blood glucose levels in male and female ΔΔ mice were normal, whereas db/db mice were already significantly diabetic (Fig. 5A and B). At later time points, however, ΔΔ animals exhibited elevated blood glucose levels similar to those of db/db mice. Similarly, male ΔΔ mice displayed significantly lower fasting glucose levels than db/db mice at 6 weeks of age (Fig. 5C), and fasted females, although not significantly different from db/db animals, also tended to have decreased blood glucose at this early age. Fasted blood glucose in ΔΔ animals of both sexes was elevated and not significantly different from db/db levels at older ages, however (Fig. 5D). These data suggest that Jak2-autonomous LepRb signals in ΔΔ mice suffice to delay the onset of diabetes compared with db/db mice, but cannot reverse the later progression to diabetes.

For female mice, there was no difference in serum insulin levels between db/db and ΔΔ mice at any age. In male mice, insulin was also similar between db/db and ΔΔ mice at 4 weeks of age, but older ΔΔ males displayed increased circulating insulin levels compared withagematched db/db males. To discriminate potential alterations in insulin clearance, we also examined serum C-peptide levels, which mirrored insulin concentrations (supplementary Fig. 1, available in an online appendix at http://diabetes.diabetesjournals.org/cgi/content/full/db09-1556/DC1). These data suggest that the relative euglycemia of ΔΔ compared with db/db animals at 4 weeks of age is not due to differences in insulin secretion (because insulin and C-peptide levels are similar between genotypes, but ΔΔ animals have decreased blood glucose at this age), but must be secondary to modest improvements in hepatic glucose output and/or insulin sensitivity. This difference is transient, however, as the increased insulin levels in older male ΔΔ animals fail to decrease blood glucose levels relative to those observed in db/db animals. No difference in β-cell mass was detected between 12-week-old ΔΔ and db/db mice (supplementary Fig. 2).

In addition, we performed glucose and insulin tolerance tests in the ΔΔ and db/db animals (supplementary Fig. 3). Although 6-week-old female ΔΔ animals displayed a diminished hyperglycemic response to the glucose tolerance test relative to db/db controls, no other differences between ΔΔ and db/db mice were observed. This suggests that the difference in glucose homeostasis between ΔΔ and db/db animals is small and not sufficient to reveal differences in the face of a substantial glucose load and/or the increased insulin resistance of advancing age.
concurrently (13,36). Indeed, chemical inhibitor studies have suggested some activation of the extracellular signal–related kinase pathway (13,36). Although the molecular mechanisms underlying Jak2-autonomous LepRb action remain unclear, several pathways could contribute. In cultured cells, the activation of Jak2 by LepRb attenuates Pomc expression. Unfortunately, the low Pomc content of db/db and ΔΔ animals and low activity of these neurons at baseline rendered the examination of POMC c-fos uninformative.

Although the overall similarity of ARC gene expression and physiology between ΔΔ and db/db mice indicates little role for Jak2-autonomous LepRb signals in ARC leptin action, the finding of decreased (worsened) Pomc mRNA expression in ΔΔ compared with db/db mice was surprising. One possible explanation for this observation is that some residual signal mediated by LepRb modestly attenuates Pomc expression and that this attenuating signal is overwhelmed under normal circumstances by the LepRb signals that enhance Pomc expression. Unfortunately, the low Pomc content of db/db and ΔΔ animals and low activity of these neurons at baseline rendered the examination of POMC c-fos uninformative.

Although the molecular mechanisms underlying Jak2-autonomous LepRb action remain unclear, several pathways could contribute. In cultured cells, the activation of Jak2 by LepRb and similar receptor mutants mediates some activation of the extracellular signal–related kinase pathway (13,36). Indeed, chemical inhibitor studies have suggested a role for extracellular signal–related kinase signaling in the regulation of autonomic nervous system function by leptin, and the autonomic nervous system underlies a major component of the leptin effect on glucose homeostasis (37). Phosphatidylinositol 3-kinase (PI 3-kinase) also plays a role in the regulation of glucose homeostasis by leptin (38–41). As we have been unable to observe the regulation of PI 3-kinase by leptin in cultured cells and the analysis of this pathway in the hypothalami of obese, hyperleptinemic mice remains problematic, the molecular mechanism by which LepRb engages this pathway remains unclear. Although difficult to test directly, it is thus possible that Jak2-autonomous LepRb signals might modulate this pathway in vivo. We have previously demonstrated that the major regulation of hypothalamic mam.

**FIG. 4.** Reduced numbers and proliferation of splenic T-cells in ΔΔ and ob/ob but not s/s or L/L mice. Spleens were isolated from the indicated genotypes of male mice, separated using autoMACS, and counted for (A) total splenocytes and (B) CD4+ cells using a flow cytometer (n = 7–22 per genotype). Data are plotted as means ± SEM; *P < 0.05 compared with wild type by one-way ANOVA and Tukey post-test. C: For proliferation assays, CD4+CD25– naive T-cells were isolated by autoMACS (n = 4–7 per genotype), incubated in the presence of bone marrow–derived dendritic cells from C57BL/6J mice and stimulated with anti-CD3e. Incorporation of 3H-thymidine (1 mCi/well) by proliferating cells was measured during the last 6 h of culture. Proliferation is expressed as a percentage of a paired wild-type sample analyzed concurrently (dashed line) and is plotted as mean ± SEM; *P < 0.05 by one-way ANOVA and Tukey post-test.

**DISCUSSION**

To determine the potential roles for Jak2-autonomous LepRb signals in leptin action in vivo, we generated a mouse model in which LepRb is replaced by a truncation mutant (LepRbΔ55) that contains within its intracellular domain only the sequences required to associate with and activate Jak2. We found that the hyperphagia, obesity, linear growth, ARC physiology, and immune function of these ΔΔ mice closely resembled that of entirely LepRb-deficient db/db mice. ΔΔ and db/db animals did demonstrate some modest differences in glucose homeostasis; however, both male and female ΔΔ mice exhibited a delayed progression to frank hyperglycemia compared with db/db mice. Taken together, these findings demonstrate that Jak2-autonomous LepRb signals may contribute modestly to the modulation of glucose homeostasis by leptin, but emphasize the necessity of signals emanating from the COOH-terminus of LepRb (beyond the Jak2-associating Box1 and Box2 motifs) for most leptin action.

The finding that 4-week-old ΔΔ mice display similar insulin and C-peptide levels as db/db animals, but exhibit improved blood glucose levels, suggests improved glucose disposal or decreased glucose production in the ΔΔ mice independent of insulin production. This is consistent with data suggesting that central nervous system leptin action suppresses hepatic glucose production, and with our previous finding that some portion of this is mediated independently of Tyr1138→STAT3 signaling (2,20,34). The ΔΔ mice progress rapidly (by 6 weeks of age) to dramatic hyperglycemia and parameters of glucose homeostasis indistinguishable from db/db animals, however. Indeed, even at 5 weeks of age, the response to a glucose bolus is comparably poor in male ΔΔ and db/db animals and barely improved in female ΔΔ compared with db/db animals. Furthermore, the increased insulin production of ΔΔ relative to db/db males at 6 weeks of age and beyond fails to ameliorate their hyperglycemia. Thus, the improvement in glucose homeostasis mediated by Jak2-autonomous LepRb signals in ΔΔ mice compared with db/db animals is very modest, as it is easily overwhelmed by a large glucose load and/or the increasing insulin resistance and diabetes of advancing age. No difference in β-cell mass was detected between ΔΔ and db/db males. The mechanism(s) mediating the increased insulin production of the ΔΔ relative to db/db males is unclear, but could represent an improvement in β-cell function due to the later time at which ΔΔ animals become diabetic or to some residual leptin action in the ΔΔ β-cell (35).

Although the overall similarity of ARC gene expression and physiology between ΔΔ and db/db mice indicates little role for Jak2-autonomous LepRb signals in ARC leptin action, the finding of decreased (worsened) Pomc mRNA expression in ΔΔ compared with db/db mice was surprising. One possible explanation for this observation is that some residual signal mediated by LepRb modestly attenuates Pomc expression and that this attenuating signal is overwhelmed under normal circumstances by the LepRb signals that enhance Pomc expression. Unfortunately, the low Pomc content of db/db and ΔΔ animals and low activity of these neurons at baseline rendered the examination of POMC c-fos uninformative.
malian target of rapamycin (mTOR), including in response to nutritional alteration, occurs indirectly, via neuronal activation (42). We examined this pathway (along with the phosphorylation of STAT3) in the hypothalamus of \( \Delta \Delta \) animals (supplementary Fig. 4), revealing the expected absence of STAT3 signaling and increased mTOR activity (secondary to the activation of orexigenic neurons) in the mediobasal hypothalamus of \( db/db \) and \( \Delta \Delta \) animals. Thus, the regulation of mTOR is similar in these mouse models.

A potential intermediate linking Jak2 activation to PI 3-kinase activation is SH2B1, a SH2 domain–containing protein that binds phosphorylated Tyr813 on Jak2 (43). Cell culture studies show that SH2B1 binds directly to Jak2, augments its kinase activity, and couples leptin stimulation to insulin receptor substrate activation, a well-known activator of PI 3-kinase (44). Indeed, SH2B1-null mice display hyperphagia, obesity, and diabetes (45). SH2B1 could also mediate other, unknown Jak2-autonomous LepRb signals.

Importantly, the phenotype of mice expressing LepRb\(^{\Delta 65}\) differs significantly from a mouse model in which LepRb\(^{Y123F}\) (mutated for the three tyrosine phosphorylation sites, but with an otherwise intact intracellular domain) replaces LepRb (22). Unlike \( \Delta \Delta \) animals, these \( Lepr^{Y123F} \) mice display improved energy homeostasis and more dramatic improvements in glucose homeostasis (both of which are sustained into adulthood), compared with \( db/db \) animals. Unfortunately, the C57 genetic background strain used to study the \( Lepr^{Y123F} \) mice not only differs compared with the C57BL/6J background that we used to study our \( \Delta \Delta \) and \( db/db \) animals, but also diverges from that of the \( db/db \) animals used as comparators for the \( Lepr^{Y123F} \) mice (22). Similarly, it is also possible that minor differences between the incipient C57BL/6J backgrounds of \( db/db \) and \( \Delta \Delta \) mice could contribute to the modest distinctions observed between these two models.

Aside from the background strain, the intriguing possibility arises that the intracellular domain of LepRb may mediate heretofore unsuspected signals independently from tyrosine phosphorylation. As it is, future studies will be needed to carefully compare the phenotype of \( Lepr^{Y123F} \), \( \Delta \Delta \), and \( db/db \) animals within the same facility and on the same genetic background; should these differences remain, further work will be necessary to confirm the importance and determine the identity of the underlying signaling.

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**FIG. 5.** Delayed onset of hyperglycemia in \( \Delta \Delta \) compared with \( db/db \) mice. A–D: Blood glucose was determined for ad libitum–fed (A and B) or fasted (5 h) (C and D) animals of the indicated genotype (wild type [WT], \( db/db \), \( \Delta \Delta \); and \( db/db \), \( \Delta \Delta \)) and sex at the indicated ages (\( n = 8–12 \) per genotype). E and F: Serum was collected from mice of the indicated genotype and sex at the indicated ages (\( n = 8–10 \) per genotype), and insulin content was determined by ELISA. All panels: Data are plotted as means \( \pm \) SEM; \( *P < 0.05, db/db \) compared with \( \Delta \Delta \) at the indicated time points by one-way ANOVA and Tukey post-test.
In summary, our findings reveal the insufficiency of Jak2-autonomous LepRb signals for the bulk of leptin action. These findings do not rule out the possibility that Jak2-autonomous signals may be required to support the action of LepRb phosphorylation, however. Indeed, our present findings suggest a modest role for Jak2-autonomous LepRb signals in the regulation of glucose homeostasis by leptin. Understanding collaborative roles for Jak2-autonomous signals in leptin action and deciphering the mechanisms underlying these signals and potential tyrosine phosphorylation–independent signals mediated by the COOH-terminus of LepRb will represent important directions for future research.

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