Novel Leptin Receptor Mutation in NOD/LtJ Mice Suppresses Type 1 Diabetes Progression

II. Immunologic Analysis

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Recently, we identified in normally type 1 diabetes–prone NOD/LtJ mice a spontaneous new leptin receptor (LEPR) mutation (designated Lepr<sup>0b-5J</sup>) producing juvenile obesity, hyperglycemia, hyperinsulinemia, and hyperleptinemia. This early type 2 diabetes syndrome suppressed intra-islet insulinis and permitted spontaneous diabetes remission. No significant differences in plasma corticosterone, splenic CD4<sup>+</sup> or CD8<sup>+</sup> T-cell percentages, or functions of CD4<sup>+</sup> T-cells in vitro distinguished NOD wild-type from mutant mice. Yet splenocytes from hyperglycemic mutant donors failed to transfer type 1 diabetes into NOD.Rag1<sup>+/−</sup> recipients over a 13-week period, whereas wild-type donor cells did so. This correlated with significantly reduced (P < 0.01) frequencies of insulin and islet-specific glucose-6-phosphatase catalytic subunit–related protein–reactive CD8<sup>+</sup> T-effector clonotypes in mutant mice. Intra-islet insulinis was also significantly suppressed in lethally irradiated NOD-Lepr<sup>0b-5J/Lt</sup> recipients reconstituted with wild-type bone marrow (P < 0.001). In contrast, type 1 diabetes eventually developed when mutant marrow was transplanted into irradiated wild-type recipients. Mitogen-induced T-cell blastogenesis was significantly suppressed when spleen T-cells from both NOD/Lt and NOD-Lepr<sup>0b-5J/Lt</sup> donors were incubated with irradiated mutant peritoneal exudate cells (P < 0.005). In conclusion, metabolic disturbances elicited by a type 2 diabetes syndrome (insulin and/or leptin resistance, but not hypercorticism) appear to suppress type 1 diabetes development in NOD-Lepr<sup>0b-5J/Lt</sup> by inhibiting activation of T-effector cells.


Leptin, mainly secreted by white adipose tissue, is well known as a hormone associated with the regulation of food intake and energy expenditure (1). The leptin receptor (LEPR) is structurally and functionally related to interleukin (IL)-6 cytokine receptor family (2,3), and the effects of leptin signaling through its receptor on immune responses have been reported (4). Leptin can upregulate alveolar macrophage phagocytic function (5) and proinflammatory cytokine secretion by peritoneal macrophages, including tumor necrosis factor-α, IL-6, and IL-12 (6). Moreover, leptin induces proliferation of the naïve CD4<sup>+</sup>CD45RA<sup>+</sup> T-cells, but not CD4<sup>+</sup>CD45RA<sup>−</sup> T-cells (7). Leptin can also polarize immune responses toward T helper-1 (Th1) cytokine production (8).

In relation to autoimmune diseases, it has been reported that both leptin-deficient (ob/ob) and LEPR-deficient (db/db) mice were resistant to experimental autoimmune encephalomyelitis (EAE) (9–11), experimentally induced arthritis (12), and hepatitis (13). However, leptin treatment restored EAE susceptibility in ob/ob mice with the Th1 cytokine promoting activity of the hormone suggested as the mechanism (9). Evidence strongly supporting a role for leptin to modulate autoimmune type 1 diabetes was the finding that early leptin treatment of postnatal NOD female mice drastically accelerated disease onset, with a Th1 deviation again proposed as the mechanism (14).

Recently, we identified in NOD/LtJ mice a spontaneous mutation in the extracellular domain of the LEPR (designated Lepr<sup>0b-5J</sup>), which produced a type 2 diabetes-like syndrome characterized by obesity, juvenile hyperglycemia, hyperinsulinemia, and hyperleptinemia (15). This new mutation produced a Gly640Val transition at a highly conserved glycine residue. Unlike the Lepr<sup>0b-1J</sup> mutation, which because of a truncated mRNA, does not produce the full-length receptor (termed Rb), the Lepr<sup>0b-5J</sup> Rb gene product is not truncated and contains intracellular JAK/STAT signal recruitment domains. Interestingly, when the Lepr<sup>0b-1J</sup> mutation was congenically transferred from the C57BLKS/J strain of origin onto the NOD background, the obesity and insulin resistance syndrome produced by this truncated mutant receptor failed to circumvent the autoimmune type 1 diabetes syndrome associated with insulitic destruction of pancreatic β-cells (16). Unlike this congenic NOD.BKS-Lepr<sup>0b-1J</sup> stock, the coisogenic NOD-
SUPPRESSED AUTOIMMUNITY IN OBESE NOD MICE

TABLE 1

No significant differences in relative proportions and total numbers \( \times 10^6 \) (in parenthesis) of splenic leukocyte subsets in NOD/Lt and NOD-Lepr\(^{db,5J}\)/Lt mice

<table>
<thead>
<tr>
<th>Mice</th>
<th>CD4 T-cells</th>
<th>CD8 T-cells</th>
<th>B-cells</th>
<th>MØ/DC</th>
<th>Granulocytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOD/Lt (total 88.0 ± 12.8)</td>
<td>36.01 ± 0.09</td>
<td>14.97 ± 0.89</td>
<td>34.95 ± 2.89</td>
<td>3.89 ± 0.20</td>
<td>4.26 ± 0.09</td>
</tr>
<tr>
<td>NOD-Lepr(^{db,5J})/Lt (total 86.9 ± 7.5)</td>
<td>37.55 ± 1.30</td>
<td>15.63 ± 0.63</td>
<td>32.22 ± 3.24</td>
<td>4.35 ± 0.09</td>
<td>3.92 ± 0.28</td>
</tr>
</tbody>
</table>

Data are mean % ± SE (n = 5) of each splenic leukocyte subset assessed in 9- to 10-week-old females by flow cytometry as described in RESEARCH DESIGN AND METHODS. MØ/DC, macrophages/dendritic cells.

Lepr\(^{db,5J}\)/Lt mice exhibited an unexpected suppression of intra-islet insulitits, allowing through \( \beta \)-cell expansion a full remission of the early onset hyperglycemia in mutant females and in some male mice (15). In the present study, we analyzed alterations in the immunologic phenotypes of NOD-Lepr\(^{db,5J}\)/Lt mice to understand how induction of a type 2 diabetes syndrome associated with both leptin and insulin resistance suppressed the autoimmune syndrome that normally develops in NOD/Lt mice.

RESEARCH DESIGN AND METHODS

Mice and reagents. NOD/Lt and obese NOD-Lepr\(^{db,5J}\)/Lt female mice were maintained in a specific pathogen-free research animal facility and allowed free access to NIH-31 pellet diet (6% fat; PMI, St. Louis, MO) and acidified drinking water. Currently, type 1 diabetes frequency is 100% in NOD/Lt females by 28 weeks and 50% in males by 37 weeks. NOD.Rag1\(^{-/-}\) females were used as recipients of adoptively transferred splenic leukocytes, and CB17 females were used as donors of allogeneic stimulator cells for mixed lymphocyte reactions. All mice were housed in a specific pathogen-free research animal facility, Monoclonal antibodies (mAbs; BD Pharmingen, San Jose, CA) used for flow cytometric analyses of splenic leukocyte subsets were fluorochrome-conjugated anti-CD4 (GK 1.5), CD8 (53-6.7), B220 (RA3-6B2), Mac-1 (M1/70), Gr-1 (RB6-8C5), and CD25 (PC61).

Antibody mixtures for staining CD4, CD8, and B-cells or macrophage/dendritic cells and granulocytes were used in leukocyte subset analyses, and antibody combinations of anti-CD4 or –CD8 and anti-CD25 were used for T-reg quantifications. The stained cells were washed and analyzed by multicolor flow cytometry and Cell Quest software (FACScalibur; BD Biosciences, San Jose, CA).

Mitogen-stimulated T-cell blastogenesis. Triplicate aliquots of 10\(^6\) splenic T-cells/well purified (>95%) by a streptavidin magnetic bead system (Miltenyi Biotec, Auburn, CA) were seeded into a round-bottomed 96-well plate with 0.25\( \mu \)g/ml phytohemagglutinin (PHA; Sigma, St. Louis, MO) or 10\(^5\) viable splenic PECs (PECs; 5 \( \times \) 10\(^5\)/well) from either NOD/Lt or NOD-Lepr\(^{db,5J}\)/Lt mice and RPMI 1640 medium with or without concanavalin A (ConA) (final 2.5 \( \mu \)g/ml) was added. After a 3-day incubation, 1 \( \mu \)l/well [\(^{3}H\)]thymidine (Perkin-Elmer Life Science, Boston, MA) was added for the final 14 h of culture, and the cells were harvested and counted with a LKB Betaload 1205 system (LKB Instruments, Gaithersburg, MD).

CD3/CD28-driven CD4+ T-cell proliferation assay and mixed lymphocyte reaction. Splenic CD4+ T-cells (purity >95%) were prepared as described above (17), and 5 \( \times \) 10\(^5\) cells/well were seeded into flat-bottomed 96-well plates precoated with anti-CD3 (145-2C11)/anti-CD28 (37.51) mAb. For mixed lymphocyte reactions, 5 \( \times \) 10\(^5\) responder T-cells/well were seeded into a 96-well plate with the same number of stimulator cells (2 Gy-irradiated splenic leukocytes) from NOD/Lt, NOD-Lepr\(^{db,5J}\)/Lt, or CB17 female donors. After 4 days, [\(^{3}H\)]thymidine incorporation was analyzed as above.

Tetramer staining of autoreactive CD8+ T-cells. Splenic β-cell autoreactive CD8+ T-cell clones were quantified by flow cytometry using previously reported tetramers (18,19). Phycoerythrin-conjugated islet-specific glucose-6-phosphatase catalytic subunit–related protein (GIPR) (KYNKAN VFL), insulin B-chain peptide 15–23 (LYLVQGERL), and irrelevant control TUM (KQAVITITL) peptide tetramers were provided by Dr. Peter Santamaria (University of Calgary, Alberta, Canada). The staining results were analyzed with >10\(^6\) live cell events gated.

Adoptive transfer of splenic leukocytes into NOD.Rag1\(^{-/-}\) recipients and cyclophosphamide treatment. Aliquots of 10\(^6\) splenic leukocytes from hyperglycemic NOD/Lt (17-week-old) and NOD-Lepr\(^{db,5J}\)/Lt (15-week-old) female donors were injected intravenously into 4- to 6-week-old NOD.Rag1\(^{-/-}\) female recipients. The recipients were then monitored for diabetes development over a 13-week follow-up period. After this, surviving non diabetic NOD.Rag1\(^{-/-}\) recipients of NOD-Lepr\(^{db,5J}\)/Lt splenic leukocytes received an intraperitoneal injection of either cyclophosphamide (200 mg/kg body wt) or PBS and were then monitored for diabetes development over the following 2 weeks.

Reciprocal bone marrow transfer. Mice were lethally irradiated with 1.2 Gy (2 \( \times \) 0.6 Gy, 4 h apart) at 4–6 weeks of age and reciprocally reconstituted with bone marrow as previously described (20). Body weight and diabetes development were monitored for up to 24 weeks after reconstitution. At diabetes onset or the end of the observation period, leukocytic reconstitution of spleen was analyzed by flow cytometry, and pancreases were removed for histologic scoring of insulitis as previously described (15).

Plasma hormone radioimmunoassay to assess diabetes type in bone marrow transfer studies. Type 1 diabetes development in NOD is reflected by insulinopenia, whereas type 2 diabetes is reflected by hyperinsulinemia and hyperleptinemia. At 8, 16, and 20 weeks after reciprocal bone marrow transfer, plasma samples were collected from all recipients, and insulin and leptin levels were determined using a rat insulin radioimmunoassay kit and a mouse leptin radioimmunoassay kit (Linco, St. Charles, MO), respectively.

Plasma corticosterone measurement. Plasma corticosterone (10 a.m. sampling) from untreated 12-week-old mice of both sexes and genotypes was determined by rat corticosterone radioimmunoassay kit (Diagnostic System Laboratories, Webster, TX).

Statistical analysis. Mann-Whitney U test was performed to assess significance of experimental differences. A P value <0.05 was considered statistically significant in group comparisons.

RESULTS

Flow cytometric comparison of splenic leukocyte subsets. No significant differences were observed between wild type and mutants in thymus or spleen wet weights. As shown in Table 1, the percentage of macrophage/dendritic cell subset was slightly increased in NOD-Lepr\(^{db,5J}\)/Lt spleens (3.89 ± 0.2% vs. 3.4 ± 0.1% in wild type), but the difference was not statistically significant. Interestingly, despite the repressed insulitis previously observed in NOD-Lepr\(^{db,5J}\)/Lt mice (15), wild-type NOD/Lt females actually had a slightly higher percentage of potentially regulatory CD4+CD25+ T-cells compared with NOD-Lepr\(^{db,5J}\)/Lt females (9.5 ± 0.7 vs. 8.0 ± 0.2%). There were no differences between wild-type and mutant mice in proportions or numbers of any other leukocyte subset.

NOD-Lepr\(^{db,5J}\)/Lt PECs suppress ConA–stimulated T-cell activation. We next assessed the ability of mutant and wild-type macrophages to serve as accessory cells in supporting ConA-stimulated T-cell proliferation. Data in Fig. 1A show that PECs from hyperleptinemic and hyperinsulinemic mutant mice significantly blunted blastogenic T-cell responses (P < 0.05). This suppressive effect was observed regardless of whether the purified T-cells were from wild-type or mutant donors. Furthermore, the same suppressive effect was observed when thiglycollate-elicited PECs were used (data not shown). Because leptin...
signaling reportedly suppresses anti-CD3– driven proliferation of human memory T-cells while stimulating that of naive human T-cells (7), we compared wild-type versus mutant CD4 T-cell activation in vitro via signaling through the T-cell receptor. Purified CD4 T-cells from both genotypes exhibited equal proliferative responses to anti-CD3/CD28 stimulation in vitro (Fig. 1B). In contrast, purified T-cell activation in a syngeneic mixed lymphocyte response (SMLR) was reduced when irradiated mutant splenocytes served as the antigen-presenting cell (APC) source for self-antigen stimulation, regardless of whether responder T-cells were from wild-type or mutant donors (Fig. 1C, difference nearing significance at \( P < 0.05 \)). No T-cell response differences were noted when allogeneic (CBA/J) stimulators were used (Fig. 1C), indicating that the SMLR differences initiated at the APC and not the T-cell level.

Reduced frequency of diabetogenic CD8 T-cell clonotypes in NOD-Lepr\(^{db-5J}/Lt\) spleen. β-Cell autoreactive CD8\(^+\) T-cell clonotypes detected by NRP-V7 (identifying the IGRP 206–214-reactive clonotypes) and insulin tetramers were significantly decreased (\( P < 0.01 \)) in spleens from NOD-Lepr\(^{db-5J}/Lt\) females compared with standard NOD/Lt controls (Fig. 2A). These two tetramers enumerate two of the most prevalent CD8 clonotypes documented in the insulitic infiltrates (19). The mean numbers of IGRP and insulin-reactive CD8\(^+\) clonotypes were 5.7- and 1.7-fold lower in NOD-Lepr\(^{db-5J}/Lt\) spleens compared with standard NOD/Lt females. Representative flow profiles are shown in Fig. 2B.

**FIG. 1.** A: Blastogenic responses of purified splenic T-cells (10\(^5\)/ml) to ConA (2.5 \( \mu \)g/ml) are significantly (\( P < 0.05 \)) suppressed by presence of irradiated PECs from NOD-Lepr\(^{db-5J}/Lt\) origin as accessory cells. D and 5J, respectively, denote NOD/Lt or NOD-Lepr\(^{db-5J}/Lt\) source of T-cells or PECs. Data are obtained from 10-week-old NOD/Lt (\( n = 3 \)) and NOD-Lepr\(^{db-5J}/Lt\) (\( n = 3 \)) females. B: No significant proliferation response differences of purified splenic CD4\(^+\) T-cells (5 \( \times \) 10\(^5\)/ml) stimulated by mAbs against CD3/CD28 in 11-week-old NOD/Lt (\( n = 3 \)) and NOD-Lepr\(^{db-5J}/Lt\) (\( n = 3 \)) females. C: Suppressed SMLR by purified splenic CD4\(^+\) T-cells (5 \( \times \) 10\(^5\)/ml) from both 10-week-old NOD/Lt (\( n = 3 \)) and NOD-Lepr\(^{db-5J}/Lt\) (\( n = 3 \)) in response to mutant APC stimulators. Unfilled and filled boxes denote wild-type and mutant donors of purified T-cell responders, respectively. Both strains showed equivalent strong responses to allogeneic CBA/J APCs. NS, no stimulator cells added.

**FIG. 2.** Autoreactive CD8\(^+\) T-cells detected by high-avidity peptide/major histocompatibility complex class I tetramers. A: Significantly reduced insulin (INS) and islet-specific glucose-6-phosphatase catalytic subunit (NRP-V7) tetramer-positive CD8\(^+\) T-cells were observed in spleens from 11- to 12-week-old NOD-Lepr\(^{db-5J}/Lt\) females compared with age-matched standard NOD/Lt controls. Data are mean percentages ± SE. *Significantly different from NOD/Lt at \( P < 0.01 \). B: Representative examples are illustrated of TUM (control), INS, and NRP-V7 tetramer staining determined by flow cytometry. Percentages of gated cells are displayed in the top right box (tetramer-binding CD8\(^+\) T-cells).
NOD.Rag<sup>−/−</sup> recipients. To assess the diabetogenic potency of splenic leukocytes from NOD-Lep<sup>db-5J/Lt</sup> donors when removed from their abnormal metabolic milieu in situ, splenic leukocytes were collected from young, hyperglycemic NOD-Lep<sup>db-5J/Lt</sup> females and adoptively transferred into NOD.Rag<sup>−/−</sup> recipients. As expected, splenic leukocytes from diabetic NOD/Lt wild-type donors transferred type 1 diabetes to six of six recipients within 5 weeks. In contrast, NOD-Lep<sup>db-5J/Lt</sup> splenocytes failed to transfer overt type 1 diabetes to any of seven recipients by 13 weeks after transfer. At necropsy after an additional 2 weeks, a moderate level of intra-islet insulitis (mean insulitis score = 1.7 ± 0.5) was observed in three of these nonhyperglycemic mutant females injected with PBS at week 13. Cyclophosphamide treatment of the remaining four mice at week 13 rendered one diabetic within 2 weeks and markedly increased intra-islet insulitis to a mean score of 3.6 ± 0.3, indicative of incipient diabetes. These results show that the Lep<sup>db-5J</sup> mutation had not deleted potential diabetogenic T-effectors but rather created an environment limiting their frequency before transfer so that homeostatic expansion of T-effectors to a critical mass was markedly prolonged.

Type 1 diabetes developed in NOD/Lt radiation chimeras transplanted with NOD-Lep<sup>db-5J/Lt</sup> marrow, but reciprocal NOD/Lt bone marrow failed to transfer type 1 diabetes to NOD-Lep<sup>db-5J/Lt</sup> recipients. Lethally irradiated NOD/Lt and NOD-Lep<sup>db-5J/Lt</sup> recipients were reconstituted with reciprocal or syngeneic sex-matched bone marrow. At 24 weeks after bone marrow transfer, final glycosuria frequencies were comparable in NOD-Lep<sup>db-5J/Lt</sup> recipients of NOD/Lt bone marrow and NOD/Lt recipients of NOD-Lep<sup>db-5J/Lt</sup> marrow (Fig. 3A). As anticipated, NOD/Lt marrow into lean NOD/Lt recipients produced the typical adult onset type 1 diabetes expected for the NOD model, whereas marrow from obese NOD-Lep<sup>db-5J/Lt</sup> donors transplanted into obese syngeneic recipients produced type 2 diabetes development in these mutants (15,21). Therefore, not surprisingly, hyperglycemia developed considerably earlier in NOD-Lep<sup>db-5J/Lt</sup> recipients of NOD/Lt bone marrow compared with wild-type NOD/Lt recipients of Lep<sup>db-5J</sup> marrow (Fig. 3A). Longitudinal changes in body weight (Fig. 3B) clearly distinguished these two reciprocal transfer sets. NOD-Lep<sup>db-5J/Lt</sup> recipients developing obesity at the start of the experiment maintained elevated body weight throughout the study period, and no spontaneous mortality was encountered. However, we elected to necropsy 3 of the 12 NOD-Lep<sup>db-5J/Lt</sup> recipient females at 17 and 19 weeks of age because of delayed-onset declines in body weight (9–11.6 g). Nevertheless the finding of low mean insulitis scores (1.5, 1.6, and 1.1) for these three individuals indicated primarily a type 2 diabetes pathogenesis of gradual β-cell failure and islet atrophy rather than a type 1 diabetes end-stage insulitis associated with rapid weight loss after hyperglycemia diagnosis. In contrast, lean NOD/Lt recipients of NOD-Lep<sup>db-5J/Lt</sup> marrow resembled NOD/Lt recipients of marrow from lean NOD donors. They remained lean and as shown below, had much more extensive insulitis.

That the NOD-Lep<sup>db-5J/Lt</sup> recipients of NOD/Lt marrow were developing the less-devastating, chronic type 2 diabetes syndrome whereas NOD/Lt recipients of NOD-Lep<sup>db-5J/Lt</sup> marrow were developing the lethal type 1 diabetes syndrome was reinforced by tracking temporal changes in plasma endocrine concentrations (Fig. 4).

Sustained hyperinsulinemia typical of unmanipulated NOD-Lep<sup>db-5J/Lt</sup> mice was observed in NOD-Lep<sup>db-5J/Lt</sup> recipients of syngeneic marrow (Fig. 4A). Although less pronounced, stable hyperinsulinemia was maintained in NOD-Lep<sup>db-5J/Lt</sup> recipients of nominally diabetogenic NOD/Lt marrow. This contrasted with the wild-type (e.g., normal) levels of plasma insulin maintained by diabetes-free mice in both lean transplant groups. As expected, elevated plasma leptin tracked with NOD-Lep<sup>db-5J/Lt</sup> recipients regardless of the source of bone marrow (Fig. 4B). The age-related decline in plasma leptin in obese recipients of NOD/Lt marrow correlated with a gradual decrease in mean body weight of this cohort (Fig. 3B).

To further address whether the diabetes development in NOD-Lep<sup>db-5J/Lt</sup> recipients of NOD/Lt marrow was type 1 diabetes, the extent of intra-islet insulitis was analyzed in each group (Fig. 5). This analysis clearly showed a significant suppression of insulitis progression in NOD-Lep<sup>db-5J/Lt</sup> recipients of either syngeneic or NOD/Lt bone marrow (mean score 0.6 ± 0.1 and 1.3 ± 0.2, respectively) compared with that in NOD/Lt recipients of NOD marrow or Lep<sup>db-5J</sup> marrow (mean score = 3.9 ± 0.1 and 3.5 ± 0.2, respectively). This suppression of intra-islet insulitis when bone marrow from either genotype was reconstituting in...
mutant recipients indicated that the host environment rather than the marrow donor was the primary determinant of the course and nature of the diabetes syndrome. **Plasma corticosterone levels were comparable in NOD/Lt and in NOD-Lepr<sup>db-5J</sup>/Lt.** Plasma corticosterone levels are significantly increased above normal in obese C57BLKS/J-Lepr<sup>db-1J</sup> (db/db) as well as C57BL/6J-Lepr<sup>ob</sup> (ob/ob) mutant mice (22–24). Female mice typically show higher corticosterone levels than males, a pattern repeated on the NOD strain background. No significant differences distinguished mutants (female, n = 3, 344 ± 76 ng/ml; male, n = 3, 143 ± 81 ng/ml) from wild type (female, n = 3, 358 ± 26 ng/ml; male, n = 3, 126 ± 76 ng/ml). Hence, hypercorticism cannot be invoked as the endocrine perturbation that is repressing activation of immune effectors.

**DISCUSSION**

An expanding body of literature is now focusing attention on the role of leptin as a regulator of proinflammatory responses and as a key player in maintenance of lymphocyte homeostasis (4,25). In contrast to human purified CD4<sup>+</sup>CD45RA (“naive”) T-cells whose anti-CD3-stimulated proliferation is stimulated by leptin (7,8), we failed to see a direct effect of leptin in vitro on proliferation of NOD T-cells in response to anti-CD3 stimulation (data not shown), possibly because of contaminating leptin present in fetal bovine serum in culture medium. The report of repressed anti-CD3 blastogenic response in B6 splenocytes treated with leptin in vitro (7) may have reflected a direct effect of leptin on APCs rather than T-cells. Our in vitro studies show that when either irradiated PECs (primarily macrophage) or irradiated splenic leukocytes from NOD-Lepr<sup>db-5J</sup>/Lt donors were coincubated with purified T-cells, they actually suppressed both mitogen-stimulated blastogenesis (Fig. 1A) and SMLR (Fig. 1C). In human and murine bone marrow cultures, leptin did not stimulate cell proliferation or survival, but rather enhanced phagocytic function and cytokine responses of PECs to parasites in vitro (26). Macrophage phagocytic activity has been reported to be markedly decreased in both leptin-deficient B6-Lepr<sup>ob</sup> mice and LEPR-Rb–deficient C57BLKS/J-Lepr<sup>db-1J</sup> mice (6). Leptin treatment normalizes defective macrophage phagocytosis in Lepr<sup>ob</sup> but not in leptin-resistant Lepr<sup>db-5J</sup> mice (6). Because reciprocal bone marrow transfer experiments did not indicate a primary defect in a hematopoietic lineage (Figs. 3 and 4), we infer that a component of the disturbed metabolic milieu suppressing autoimmune activation of T-effectors is the leptin resistance generated by the mutation in the extracellular (Ra) domain of the Lepr<sup>db-5J</sup> receptor. Preliminary transfection studies in COS7 cells indicate reduced leptin-binding affinity of both short form (LEPR-Ra) and long (signaling) form (Rb) of the Lepr<sup>db-5J</sup> receptor. Therefore, we infer that either the suppressive effects observed are an incomplete function of long-form receptor by low binding affinity of leptin due to the mutation (glycine to valine residue at 640 residue) in the extracellular domain or else represents a receptor-independent action of leptin.

There are several phenotypic features of NOD-Lepr<sup>db-5J</sup>/Lt mice that set them apart from the well-characterized C57BLKS/J-Lepr<sup>db-1J</sup> mice. Specifically, the former retain reproductive competence and do not develop hypertriglyceridemia (15). Furthermore, we now demonstrate that NOD-Lepr<sup>db-5J</sup>/Lt mice do not develop hypercorticism, a phenotype characterizing C57BLKS/J-Lepr<sup>db-1J</sup> and C57BL/6J-Lepr<sup>ob</sup> mice (23). These differences presumably derive from the site of the mutations (e.g., the extracellular domain) of the LEPR-Rb receptor.

**FIG. 4. Comparisons of insulin (A) and leptin (B) levels in recipients of reciprocal bone marrow transfer between NOD/Lt and NOD-Lepr<sup>db-5J</sup>/Lt females.** Data were obtained at 8, 16, and 20 weeks after transfer and expressed as means ± SE. D, NOD/Lt donor or recipient; 5J, NOD-Lepr<sup>db-5J</sup>/Lt donor or recipient. ‡Significantly different from age-matched 5J recipients at P < 0.01. §Significantly different from age-matched D → 5J recipients at P < 0.01. !Significantly different from age-matched D → D recipients at P < 0.001.

**FIG. 5. Comparisons of pancreatic insulitis in recipients of reciprocal bone marrow transfer between NOD/Lt (D) and NOD-Lepr<sup>db-5J</sup>/Lt (5J) females.** The insulitis of each individual islet is graded into 0 (normal), 1 (peri-insulitis), 2 (infiltration < 25% of islet mass), 3 (infiltration between 25 and 75% of islet mass), and 4 (islet destruction). Percent of islets was calculated for each grade in each recipient. *Significantly different from D → D recipients at P < 0.001. ‡Significantly different from 5J → D recipients at P < 0.001.
domain of NOD-Lepr<sup>db-5J/Lt</sup> receptor that does not prevent transcription of a full-length receptor with an intracellular JAK/STAT signaling domain (15) that is missing in C57BLKS/3-Lepr<sup>db-13</sup> mice. Recently, a LEPR Rb mutation has been generated in the murine STAT3 recruitment domain by site-specific mutagenesis (24,27). Like NOD-Lepr<sup>db-5J/Lt</sup> mice, these mice retain reproductive function and exhibit a less severe insulin resistance syndrome than C57BL6/J-Lepr<sup>db-14</sup> mice, suggesting that certain effects of leptin on glucose homeostasis may be mediated by a route other than through Rb/STAT3 signaling. It remains to be demonstrated whether the immune suppressive actions of the Lepr<sup>db-5J</sup> mutation in NOD mice are mediated by receptor-dependent (presumably decreased function of leptin via the long Rb isoform?) or -independent mechanisms. The finding that the effect of the Lepr<sup>db-5J</sup> mutation on the course of diabetogenesis in NOD mice is seemingly quite different from that reported for the Lepr<sup>db-13</sup> mutation (16) might suggest that some degree of Rb signaling is the salient feature distinguishing the Lepr<sup>db-5J</sup> from Lepr<sup>db-14</sup> mutation. Female mice exhibit higher circulating leptin concentrations in plasma than do males. That the increased leptin concentrations naturally present in NOD females compared with females of other strains was a contributor to the female bias in type 1 diabetes development in this model was supported by the finding that postnatal administration of recombinant leptin accelerated type 1 diabetes onset in NOD females, but not males (14). At the present time, it remains unclear whether loss of leptin sensitivity conferred by the Lepr<sup>db-5J</sup> mutation or some other disturbed metabolic parameter (chronic hyperinsulinemia?) underlies the suppressed insulitis development and autoimmune destruction of Lepr<sup>db-5J</sup> β-cells. Nevertheless, the present study demonstrates an important contribution of an intact LEPR in the normal course of type 1 diabetes progression in NOD mouse model.

In standard NOD/Lt mice, CD8 T-cells reactive against either IGRP or insulin B chain peptide represent a major proportion of islet-infiltrating T-cells as insulitis progresses (19). The significant decrease in these diabetogenic clonotypes in spleens of NOD-Lepr<sup>db-5J/Lt</sup> is an excellent indicator of downregulated autoimmunity (Fig. 2). Early administration of insulin to young prediabetic NOD mice retards onset of insulin and diabetes (28). Conceivably, the spontaneous hyperinsulinemia produced by the Lepr<sup>db-5J</sup> mutation could have produced central deletion or peripheral anergy of insulin-reactive clones. In the case of CD8 T-cells specific for insulin B chain 15–23, tetramer staining showed they were present in mutant spleens but in reduced numbers (Fig. 2). This was also the case of IGRP-reactive CD8 clonotypes (Fig. 2). Hence, T-cell tolerance mediated through central deletion did not appear to be occurring. Moreover, insulin autoantibodies were detected in some wild-type and mutant mice (data not shown), indicating absence of humoral tolerance, at least to insulin. The finding that splenic leukocytes from obese donors adoptively transferred insulitis, albeit at a retarded rate, showed that diabetogenic clonotypes were present but were not at levels comparable with normoinsulinemic, normoantibodyemic wild-type controls. In part, this decreased level of diabetogenic T-cells might be attributed to the suppressive effects of Mac-1–positive/Gr-1–negative cells (both macrophage and dendritic cells) in peripheral lymphoid tissues. Another aspect of the hyperinsulinemic environment that might contribute to repressed immune effector activation is a previous demonstration in vitro that insulin is a potent macrophage chemoattractant (29). Possibly, the systemic hyperinsulinemia destroys what otherwise would be an insulin gradient that macrophages follow to extravasate into the islets during the earliest phase of insulitis initiation (30).

When type 1 diabetes is retarded by experimental manipulation of the NOD model, CD4<sup>+</sup>CD25<sup>+</sup> Tregs are often implicated in the protective mechanism (31–33). It is especially tempting to invoke upregulation of T-reg function as the mechanism underlying reduced insulitis and suppression of type 1 diabetes in NOD-Lepr<sup>db-5J/Lt</sup> mice in light of a recent study showing that serum leptin inversely correlates with T-reg proliferation in relapsing-remitting multiple sclerosis patients and in an EAE mouse disease model (34). This latter study reported a higher percentage of T-reg cells in lymphoid organs of leptin-deficient Lepr<sup>db</sup> or leptin-resistant Lepr<sup>db</sup> mice than in controls (34). Disease suppressive contributions of this T-cell subset are usually demonstrated in the context of homeostatic expansion after adoptive co-transfer with T-effectors into immunodeficient NOD-Ptkdc<sup>scid</sup> or NOD-Rag recipients (31,35). In contrast to the slight increase of splenic macrophage/dendritic cell percentages and total numbers in NOD-Lepr<sup>db-5J/Lt</sup> mice, the CD4<sup>+</sup>CD25<sup>+</sup> splenic T-cell subset was actually decreased in mutant mice of both sexes. We have previously shown that defects in immune suppressor function in NOD/Lt mice was associated with defects in APC co-stimulation (36). In that earlier study, the SMLR was used as a measure of self-major histocompatibility complex–restricted T-suppressor function. Our finding that the SMLR of NOD-Lepr<sup>db-5J/Lt</sup> mice is even lower than that of NOD/Lt wild-type mice (Fig. 1C) strongly suggests that T-reg activation is not the mechanism underlying retarded type 1 diabetes in this model. Our finding that purified mutant T-cells activated in vitro in the absence of mutant APCs are indistinguishable in proliferative response to wild type (Fig. 1B), whereas their blastogenic responses are suppressed by syngeneic APCs (Fig. 1C), suggests that an APC rather than a T-cell elaborated factor or factors is involved. Interestingly, “viable motheaten” mice with a defect in their SHP-1 hemopoietic stem cell phosphatase gene show a similar suppressive macrophage phenotype (37). Treatment of cultures with anti-transforming growth factor (TGF)-β alleviated their suppressive potency (38). However, TGF-β1 is unlikely to be a factor for the type 1 diabetes suppression of NOD-Lepr<sup>db-5J/Lt</sup> because we observed comparable TGF-β1 (by ELISA) in lipopolysaccharide-stimulated supernatants from both NOD/Lt and NOD-Lepr<sup>db-5J/Lt</sup> bone marrow-derived macrophage cultures (data not shown). Likewise, multiplex bead assay for IL-18, IL-6, IL-10, tumor necrosis factor-α, IL-12p70, and interferon-γ concentrations in the same supernatants indicated no significant differences (data not shown), such that a Th1 to Th2 deviation often associated with suppression of NOD diabetogenesis was not indicated. Similarly, no differences in secreted eicosanoids (prostaglandin E2, leukotriene B4, 15S-HETE, and lipoxin A4) in the same supernatants were detectable (data not shown). T-cell activation and hepatocyte killing in a model of ConA-induced hepatitis was reduced by adiponectin, raising the possibility that this or other adipokines elevated in the obese NOD stock may have been immunoprotective (39).

In summary, we have found that superimposition of a leptin-resistant obesity syndrome in NOD/Lt mice that normally develop type 1 diabetes at high frequency pro-
roduces a type 2 diabetes syndrome that suppresses levels of autoimmune T-effectors. Decreases in numbers of diabetogenic T-cells in obese mutant mice correlated with failure of their splenic leukocytes to adoptively transfer type 1 diabetes into immunodeficient recipients within a standard time frame, although immune effectors were clearly present. Reciprocal bone marrow reconstitution experiments demonstrated the primary role of mutation-induced disturbance of the endocrine/metabolic milieu rather than defects expressed at the level of hemopoietic stem cell derivatives. APCs isolated from these leptin- and insulin-resistant obese mutant mice suppressed T-cell proliferative responses in vitro. Although type 1 diabetes is considered primarily a consequence of an imbalanced immune system and type 2 diabetes, an imbalanced endocrine/metabolic system, the endocrine system (including sex steroids, glucocorticoids, leptin, and insulin) shapes immune responsiveness in type 1 diabetes; and reciprocally, proinflammatory reactants released by the immune system contribute to the metabolic defects associated with type 2 diabetes. The present study emphasizes the importance of gaining a better understanding of the interplay between the endocrine and immune systems in both healthy and disease states.

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