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Butyrophilin-like 2 Modulates B7 Costimulation To Induce Foxp3 Expression and Regulatory T Cell Development in Mature T Cells

Ryan M. Swanson,*1 Marc A. Gavin,*1 Sabine S. Escobar,* James B. Rottman,† Brian P. Lipsky,* Shishir Dube,‡ Li Li,* Jeannette Bigler,§ Martin Wolfson,* Heather A. Arnett,*2 and Joanne L. Viney*2,3

Naive T cell activation involves at least two signals from an APC, one through the TCR via interaction with peptide–MHC complexes and a second through ligation of CD28 with B7 ligands. Following activation, T cells upregulate a host of other membrane-bound costimulatory molecules that can either promote or inhibit further T cell maturation and proliferation. In some cases, it is necessary to attenuate T cell activation to prevent deleterious inflammation, and inhibitory members of the B7/butyrophilin family of ligands have evolved to balance the strong stimuli the activating B7 ligands confer. Human genetic association and in vitro studies have implicated one such ligand, BTNL2, in controlling inflammation at mucosal surfaces. In this study, we show that recombinant mouse BTNL2 modifies B7/CD28 signaling to promote expression of Foxp3, a transcription factor necessary for regulatory T cell (Treg) development and function. BTNL2 blocks Akt-mediated inactivation of Foxo1, a transcription factor necessary for Foxp3 expression. Immunophenotyping and gene profiling reveal that BTNL2-induced Treg share many properties with natural Treg, and in vivo they suppress enteritis induced by mouse effector T cells. These findings describe a mechanism by which environmental Ag-specific Tregs may be induced by APC expressing specific modulators of costimulatory signals. The Journal of Immunology, 2013, 190: 2027–2035.

R egulatory T cells (Treg), identified by their requisite transcription factor Foxp3, are a subset of CD4 T cells that have become central to our understanding of immune tolerance. Foxp3 is induced in thymic Treg precursors, generating so-called natural Treg (nTreg) that populate peripheral lymphoid and nonlymphoid organs and chronically suppress deleterious inflammatory responses against self tissues, environmental Ags, and commensal microorganisms. Foxp3 can also be induced in naive CD4 cells under appropriate conditions in vitro (1, 2) and in vivo (3, 4), generating induced Treg (iTreg). Although Treg specific for peripheral neo-Ag can originate from the pre-existing repertoire of nTreg, it has recently become clear that colonic Treg specific for commensal bacteria arise from conversion of naive CD4 T cells into iTreg (5). Several signaling pathways contribute to Foxp3 induction, including those downstream of the TCR (6, 7), the CD28 coreceptor (8), and the receptors for TGF-β and IL-2 (9–11). Elucidating how each of these pathways acts on the Foxp3 promoter and discovery of novel factors that promote iTreg development are areas of intense investigation in Treg biology.

Important modulation of TCR-mediated T cell activation is provided by the CD28 family of receptors, in which CD28 and ICOS potentiate T cell proliferation and differentiation and CTLA-4, PD-1, and BTLA attenuate these responses. It has become evident in recent years that this regulation of TCR signaling is critical not only for effector T cell function, but also for Treg development (12, 13). CD28 signaling in the thymus directly contributes to Foxp3 induction (8). Diabetes-prone NOD mice deficient for CD28 or the CD82 ligands, B7-1 and B7-2, develop exacerbated diabetes resulting from decreased numbers of Treg (14). More recent work has suggested a role for another B7 family member, the PD-1 ligand PD-L1, in Foxp3 induction in peripheral naive T cells both in vivo and in vitro (15). Whereas high concentrations of TGF-β are well known to induce Foxp3 expression in CD3/CD28-stimulated T cells (1), recombinant PD-L1 coimmobilized with anti-CD3 and anti-CD28 was found to synergize with suboptimal quantities of TGF-β to generate suppressive Foxp3+ iTreg. Another recent report demonstrated PD-L1–mediated conversion of human Th1 cells into iTreg, suggesting that this biology is conserved between mice and humans (16). The mechanism by which inhibitory costimulatory molecules participate in Treg differentiation remains to be defined; however, a role for reduced activity of the PI3K/Akt/mTOR pathway is supported (15).

Several other inhibitory B7 or B7-like molecules have been identified to date, all of which suppress T cell activation through unknown receptors. These include B7H3, B7H4, B7S3, and members of the butyrophilin family of B7-related ligands (17–20). Butyrophilin-like 2 (BTNL2) is one inhibitory ligand of particular interest due to its strong genetic association with human autoimmune and inflammatory disease (21–24). BTNL2 is strongly expressed in epithelial cells of the small intestine, and expression
is upregulated in mouse models of inflammatory bowel disease (22). Because of its expression in the gut and its functional activity in limiting T cell activation, BTNL2 is thought to play a role in limiting unwanted inflammation directed against commensal bacteria or dietary Ag.

In this work, we demonstrate that BTNL2 costimulation during T cell activation promotes de novo Foxp3 expression and the development of suppressive Treg. Our studies provide new insight into how opposing activating and inhibitory signals generated by the B7/butyrophilin family of ligands can be integrated to dictate T cell differentiation and promote dominant tolerance.

Materials and Methods

Animals

Six- to 12-wk-old female C57BL/6 (Taconic), C57BL/6.SIL (The Jackson Laboratory), and C57BL/6 RA/G2 knockout (KO) (Taconic) mice were housed under specific pathogen-free conditions at the Amgen animal facility. Studies were conducted in accordance with National Institutes of Health guidelines for the proper use of animals in research and Amgen Institutional Animal Care and Use Committee–approved protocols.

Proteins and plate coating for T cell stimulations

Various reagents were purchased from commercial sources, including anti-mouse CD3 (clone 145-2C11; BD Biosciences), murine rB7-1.Fc (R&D Systems, carrier-free), murine rB7-2.Fc (R&D Systems, CF), and purified human IgG (Sigma-Aldrich). Murine rB7TFc was prepared at Amgen, as previously described (22). Proteins were immobilized to flat-bottom 96-well plates (Costar, Corning 3595) in 100 µl PBS overnight. Stimulation coating contained 2 µg/ml total protein, consisting of 2 µg/ml anti-CD3 and 20 µg/ml rB7/rBTNL2/human IgG. Equivalent m.w. ratios were plated at 2 molecules of anti-CD3/10 molecules of rBTNL2.Fc/2.5 molecules of rB7.Fc, and equal loading achieved by offsetting with the proper amount of human IgG. Before adding cells to coated plates, unbound protein was washed off twice with 200 µl PBS.

CD4 T cell isolation

Single-cell suspensions were prepared from spleens and lymph nodes from female C57BL/6 mice (6–8 wk old; Taconic). CD4 cells were purified using the EasySep mouse CD4 T cell enrichment kit (Stem Cell Technologies). In some experiments, Treg were depleted first (biotin anti-mouse CD25, eBioscience [PC61.5]; anti-biotin beads and AutoMACS separation, Miltenyi Biotec), followed by CD4-positive selection (mouse CD4 beads; Miltenyi Biotec). For all 96-well stimulations, 100,000 purified CD4 T cells were added per well.

In vitro stimulations

CD4 cells were cultured in a final volume of 200 µl complete RPMI 1640 medium containing 10% FBS (HyClone), 1 mM sodium pyruvate (Invitrogen), 100 µM nonessential amino acids (Invitrogen), 0.1% 2-ME (Invitrogen), 100 U/ml penicillin (Invitrogen), and 2 mM L-glutamine (Invitrogen). Twelve-well tissue culture plates (Falcon) were coated with anti-CD3, rB7, rBTNL2, and human IgG at molecular ratios indicated in T cell stimulation methods above. For 6-well plates, 3.33 ml PBS with protein was incubated overnight before washing wells twice with PBS and adding cells. CD4 cells were purified, as described above, and 10 million cells were added per well. Plates were immediately spun down at 750 rpm to initiate uniform exposure to immobilized protein stimulation, and plates were moved to a 37˚C incubator. Two minutes prior to the chosen time point, plates were spun at 1200 rpm for 1.5 min. Media was aspirated off wells, plates were incubated on ice, and 500 µl cell lysis buffer (Clontech) containing protease and phosphatase inhibitors (Ferri) was added to wells. Plates were incubated on ice for 30 min before lyses were transferred to Eppendorf tubes for clearing by centrifugation. For Western blotting, reduced lysates containing equal cell equivalents were loaded onto 4–20% SDS-PAGE electrophoresis gels, and resolved proteins were transferred onto nitrocellulose membranes using an iBlot Dry Blotting System (Invitrogen). Membranes were probed with the Abs rabbit anti–phospho-FOXO1 (Thr24)/FOXO3a (Thr32), rabbit anti–phospho-FOXO1 (Ser256), rabbit anti-FOXO1 (C29H4), rabbit anti–pan-activin receptor, rabbit anti–phospho-Akt (Ser473) (D9E), and rabbit anti–pan-Akt (11E7) from Cell Signaling Technology using the manufacturer’s suggested concentrations and protocols. Membranes were developed using Amersham ECL Western blotting reagents (GE Healthcare).

FACS analysis

Purified CD4 cells harvested from plate stimulations were spun and resuspended in FACS buffer containing PBS with 1% BSA and 0.1% sodium azide. Surface staining was performed with PE anti-mouse CD25 (PC61; BD Biosciences), PE anti-CD62L (MEL-14; BD Biosciences), PE anti-CD69 (FJK-244), PE anti–pan-activin receptor, PE anti–phospho-Akt (Ser473) (D9E), and PE anti–pan-Akt (Th11E7) from Cell Signaling Technology using the manufacturer’s suggested concentrations and protocols. Membranes were developed using Amersham ECL Western blotting reagents (GE Healthcare).

In vivo suppression assay

Twelve-well tissue culture plates were coated overnight with 1 ml PBS containing 2 µg/ml anti-CD3 (2C11; BD Biosciences) and an equivalent of 20 µg/ml human IgG. For the anti-CD3 plus rB7-2.Fc stimulation, this was 3 µg/ml rB7-2.Fc plus 15.5 µg/ml human IgG, and for anti-CD3 plus rB7-2.Fc plus rBTNL2.Fc, this was 3 µg/ml rB7-2.Fc plus 11 µg/ml rBTNL2.Fc. For the anti-CD3 plus rBTNL2.Fc stimulation, this was 3 µg/ml rB7-2.Fc plus 15.5 µg/ml human IgG. Cells were isolated from C57BL/6 (CD45.2) spleen and lymph nodes. CD25+ cells were removed by positive selection (CD25 beads; Miltenyi Biotec), and remaining CD4 cells purified by positive selection (CD4 beads; Miltenyi Biotec). One million CD4 cells were added to 12-well plates, and cells were cultured in 1 ml media containing 0.36 ng/ml rTGF-β and 20 ng/ml murine IL-2. On day 4, 0.5 ml exhausted media was removed from wells, and 1 ml fresh media with rTGF-β and IL-2 at the same concentrations as above was added to cultures. This was performed on day 5, all cultures harvested on day 12, and stained with PE anti–Foxp3 (FJK-169), PE anti–CD39 (24DM51; eBioscience), and PE anti–GARP (YG1C8; eBioscience). Cells were incubated with Abs at 5 µg/ml for 30 min on ice, followed by two washes with FACS buffer. Subsequent intracellular staining was performed with the Foxp3 intracellular staining kit (eBioscience), according to manufacturer’s recommendation. Allophycocyanin or PE anti-mouse Foxp3 (FK4-169; eBioscience) was incubated with cells for 30 min at 2.5 µg/ml on ice. Following intracellular staining, cells were washed twice and fixed with Cytotox (BD Biosciences) before reading on FACS Calibur (BD Biosciences).
cells were prepared by CD4/CD25-positive selection (Miltenyi Biotech) of cells isolated from C57BL/6 lymph nodes. Unactivated effector CD4 T cells were prepared from spleen and lymph nodes from congenic C57BL/6 SJL mice (CD45.1+ by depleting CD25+ cells first and then positively selecting CD4 cells. A 1:1 ratio of suppressor/effect cell in 200 μl PBS was injected i.v. (1 million suppressors, 1 million effectors) into C57BL/6 Rag2 KO hosts. Animal weights were monitored twice weekly for 2 mo, and host animals were euthanized on day 58, harvesting spleen, mesenteric lymph node, and peripheral lymph node (cervical + inguinal) as well as the entire small intestine and colon for histology. Cells were isolated from spleen and lymph nodes and quantitated on VioCell, and remaining cells were stained for CD4, CD8, CD45.2, and CD25. Two sections each of duodenum, jejunum, ileum, proximal, and distal colon were collected and fixed in 10% neutral buffered formalin for 24 h. Tissues were subsequently dehydrated through graded alcohols and xylene and embedded in paraffin. Tissues were sectioned at 5 μm, deparaffinized, stained with H&E, and coverslipped. Sections were examined by a pathologist and assigned a score reflecting the degree of epithelial hyperplasia and inflammation according to the following criteria: grade 0 = no change over normal; grade 0.5 = minimal inflammation, no hyperplasia; grade 1.0 = mild inflammation, no hyperplasia; grade 1.5 = mild inflammation, minimal hyperplasia; grade 2.0 = mild/moderate inflammation, minimal hyperplasia; grade 2.5 = mild/moderate inflammation, mild hyperplasia; grade 3.0 = moderate inflammation, mild/moderate hyperplasia; grade 3.5 = moderate inflammation, moderate hyperplasia; grade 4.0 = moderate/mark mild inflammation, moderate hyperplasia; grade 4.5 = marked inflammation, moderate/mark mild hyperplasia, ulceration; grade 5.0 = marked inflammation, marked hyperplasia, ulceration. The inflammation scores assigned to the tissues in each pair were averaged and the average plotted. Statistical differences between groups were determined by using the Kruskal Wallis test with Dunn’s multiple comparisons.

Results

BTNL2 inhibits cytokine production and Akt and Foxo phosphorylation, and promotes Fopx3 expression

A method often employed to assess costimulatory molecule function is T cell stimulation with beads or surfaces coated with anti-CD3 and coimmobilized costimulatory proteins. Our group and others have previously published that immobilized rBTNL2.Fc and anti-CD3 severely limit the ability of mouse primary T cells to become activated, proliferate, and produce inflammatory cytokines (21, 22, 25). A second signal in the form of anti-CD28 has been shown to partially restore T cell activation in the presence of BTNL2 (21, 25), and inhibition by BTNL2 can be further overcome by exogenous IL-2 (21, 25). We investigated the ability of immobilized B7 ligands, in the form of rB7-1.Fc or rB7-2.Fc, to activate primary murine T cells in the presence of rBTNL2. Fc. Fig. 1A shows typical results from these experiments. T cell proliferation was induced with anti-CD3 alone, augmented with immobilized rB7, and inhibited with rBTNL2. Coimmobilization of rB7 and rBTNL2 at the ratios described reversed BTNL2 inhibitory activity, restoring T cell proliferation. Although rB7 stimulation reversed the proliferative block induced by rBTNL2, we hypothesized that rBTNL2 may modulate other components of rB7 costimulation and alter the phenotype of the activated T cells. Indeed, interrogation of multiple cytokines revealed that rBTNL2 still delivered a suppressive signal in the presence of B7 cositulation, resulting in greatly reduced secretion of IL-2, IL-13, IL-17, IFN-γ, and several other cytokines (Fig. 1B). In a pilot experiment designed to examine the effects of rBTNL2 on global gene expression induced by anti-CD3 alone, we observed that rBTNL2 not only suppressed the transcription of the majority of anti-CD3–induced genes, but also modulated a small set of genes characterized as targets of the Foxo1 and Foxo3 transcription factors (Supplemental Fig. 1). As Foxo transcription factors are known to be inactivated by Akt phosphorylation, we examined the phosphorylation status of Akt and Foxo1 in similar T cell stimulation conditions. Whereas anti-CD3/rB7-2 stimulation resulted in strong Akt phosphorylation at Ser473, inclusion of rBTNL2 inhibited Akt phosphorylation, resulting in phospho-Ser473 levels similar to that found in unstimulated T cells (Fig. 2A). A more striking effect of rBTNL2 on this pathway was observed by monitoring Foxo1 phosphorylation at the Akt target residues Thr32 and Ser256. In this study, inclusion of rBTNL2 with anti-CD3/rB7-2 stimulation resulted in complete inhibition of Foxo1 phosphorylation at these sites (Fig. 2B). Together, these results show that BTNL2 stimulation in the context of CD3/CD28 ligation selectively inhibits Akt signaling and cytokine production, while leaving pathways responsible for T cell proliferation intact.

Although the importance for Foxo transcription factors in maintaining cellular senescence and survival has been appreciated for several years, a role in promoting Foxp3 expression and Treg development has only recently been described (26–29). Foxo1 and Foxo3a were found to cooperate with TGF-β–induced signals to promote Foxp3 transcription and iTreg differentiation. To examine whether BTNL2 would also synergize with TGF-β to induce Foxp3 expression, CD4+ T cells were stimulated in the presence of low concentrations of TGF-β. Because BTNL2 inhibits IL-2 production (Fig. 1B) (21, 22), and because IL-2 is an important Treg growth factor, exogenous IL-2 was included to more directly assess the effects of rBTNL2 on iTReg differentiation. When T cells were stimulated with anti-CD3 alone or with rB7-1 or rB7-2, considerable T cell expansion was observed by day 4 (Fig. 3A; from 0.3 million to ~1.5 million CD4+ T cells). Inclusion of rBTNL2 in the stimulation conditions inhibited expansion only in the absence of CD28 ligands, similar to results shown in Fig. 1A, where proliferation was monitored by [3H]dT incorporation. Negligible total numbers of Foxp3+ cells were recovered from any of these six stimulation conditions (Fig. 3A). When exogenous IL-2 was added to the cultures, very similar results were obtained (Fig. 3B). Addition of a suboptimal concentration of TGF-β induced <20% Foxp3+ cells in conditions without rBTNL2. In the presence of rBTNL2, however, more than half of the cells expressed Foxp3 (Fig. 3C). Whereas the combination of TGF-β and rBTNL2 limited overall T cell expansion (Fig. 3C), addition of IL-2 restored growth without altering the percentage of Foxp3+ cells (Fig. 3D). In contrast, addition of IL-2 to cultures stimulated with anti-CD3 and TGF-β alone resulted in twice the number of Foxp3+ T cells without increasing the total number of TGF-β– induced Foxp3+ cells. Very similar results were obtained when CD25-depleted CD4 cells were used as the starting population, indicating the large number of Foxp3+ cells recovered after stimulation with rBTNL2 did not result from rapid expansion of pre-existing Treg (Supplemental Fig. 2). These data show that rBTNL2 can function in concert with B7 costimulation and TGF-β to induce Foxp3 expression without impairing a T cell’s proliferative potential.

Foxp3 induction in naive T cells is a coordinated event in which the strength of TCR and CD28 signals is integrated with the surrounding cytokine and metabolic milieu. Decreasing TCR/CD28 agonism levels are known to support Foxp3 induction in the presence of TGF-β (30). Because BTNL2 is a relatively large protein, and the receptor for BTNL2 on T cells has not been identified, it was important to demonstrate that recombinant BTNL2 protein did not decrease anti-CD3–driven TCR agonism through nonspecific steric hindrance and resulting in upregulated Foxp3 expression. To address this issue, we chose two control proteins that are known to bind receptors on CD4 T cells and have the same predicted m.w. as rBTNL2.Fc: rICAM.Fc and anti-CD132. These 150-kDa control proteins were coimmobilized in the same manner as rBTNL2 with anti-CD3 and rB7-2, and Foxp3 percentages and total numbers were evaluated. Supplemental Fig. 3 shows that even though molecular equivalents of human IgG,
rICAM, and anti-CD132 were plated at the same anti-CD3/rB7 ratios as rBTNL2, only CD4 cultures containing rBTNL2 induced Foxp3 percentages above 8% (BTNL2 34%, IgG 8%, rICAM 1%, anti-CD132 6%). Additionally, the BTNL2/B7 cultures resulted in a 2-fold expansion of total Foxp3+ CD4 T cell numbers compared with the control stimulations. Another method employed to investigate BTNL2’s specific effects on Foxp3 induction was to alter the anti-CD3/B7 stimulation levels in the presence or absence of rBTNL2.

FIGURE 1. BTNL2 inhibits CD4 T cell cytokine production without impacting proliferation in the context of B7 costimulation. Purified mouse CD4 T cells were stimulated with immobilized reagents, as shown. (A) Proliferation was measured by pulsing cultures with [3H]thymidine on day 3. Error bars represent SEM of triplicate wells. (B) Cytokines were analyzed in supernatants harvested prior to measuring proliferation on day 3. Data shown are representative of at least two experiments.
BTNL2. Variable concentrations of both anti-CD3 and rB7 were plated ± rBTNL2 and compared with the baseline conditions identified in Fig. 3 (Supplemental Fig. 4). Inclusion of BTNL2 increased Foxp3 percentages at all anti-CD3 and rB7 stimulation conditions. Total Foxp3+ CD4 numbers were also increased compared with the same stimulations without rBTNL2. The only exception was the lower anti-CD3 concentration of 0.5 μg/ml, which still had the higher percentage of Foxp3+ cells in the presence of BTNL2, but did not generate greater total Foxp3+ cell numbers, indicating that the BTNL2 inhibitory effect did not allow for CD4 T cell expansion at lower TCR agonism strength as would be expected from our previous publication (22).

Foxp3+ CD4 T cells induced with BTNL2/B7 possess characteristics of nTreg

To further characterize the Foxp3+ cells generated with rBTNL2/rB7 in the presence of exogenous TGF-β and IL-2, we examined the surface markers of cells generated from these stimulation conditions. Some markers characteristic of nTreg were strongly upregulated in rBTNL2/rB7–stimulated cells (Fig. 4). The most dramatic example was CD62L, the gene for which (Sell) is a target of Foxo1 transcriptional activation. Whereas activation of cells with anti-CD3 or anti-CD3 plus rB7 downregulated CD62L surface expression, addition of rBTNL2 promoted maintenance of CD62L expression on ~50% of the cells. High CD62L expression was observed in both Foxp3+ and Foxp3− populations, suggesting Akt inhibition and Foxo1 activation were not dependent on Foxp3 expression.

CD39, an ectonucleotidase that converts AMP to adenosine at the cell surface, has been reported to be a marker, as well as a functionally suppressive molecule, on both human and mouse Treg (31). GARP is a surface receptor that binds latent TGF-β and has been shown to be a specific marker for activated Treg (32, 33). The genes for both of these markers are positively regulated by Foxp3 (34, 35). Both CD39 and GARP were more highly expressed on Foxp3+ cells in all stimulation conditions; however,
BTNL2 further upregulated their expression on both Foxp3+ and Foxp3- cells, suggesting that Foxp3 and BTNL2 may independently promote their expression (Fig. 4). These data show BTNL2 can induce specific surface T cell markers that are shared with nTreg.

To further examine the effects of BTNL2 stimulation on T cell phenotype, we compared global gene expression profiles of CD25-depleted CD4 T cells stimulated with anti-CD3 and rB7-2 with or without rBTNL2. Cultures were also supplemented with IL-2 and low concentration TGF-β. On day 4, T cells were characterized by flow cytometry. The percentages shown in the larger font were calculated as the percentage of cells expressing the indicated surface marker among either Foxp3+ or Foxp3- cells. Data shown are representative of two experiments.

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CD4 cells activated in the presence of rBTNL2 and rB7-2 control effector T cell expansion and enteritis when cotransferred into Rag2-deficient hosts

We next assessed whether BTNL2-induced iTreg possessed suppressor activity. Because of a predicted role for BTNL2 in intestinal immune tolerance, we were interested in using an in vivo system in which intestinal inflammation could be induced. Adopitive transfer of effector T cell populations into immunodeficient hosts is a common approach for inducing enteritis/colitis (36). Suppression of inflammation induced by transfer of congenically marked CD25-CD4+ effector cells into Rag2-deficient hosts was assessed for three separate test suppressor populations, as follows: 1) purified CD25-CD4+ nTreg (88% Foxp3+); 2) CD25-CD4+ cells stimulated with anti-CD3/rB7-2 (2% Foxp3+); or 3) CD25-CD4+ cells stimulated with anti-CD3/rB7-2/rBTNL2 (48% Foxp3+). The stimulation conditions for generating the latter two suppressor populations also included IL-2 and low-dose TGF-β. Following transfer of 1 million suppressor cells and 1 million effector cells, host body weight and stool were monitored for signs of enteritis over a 2-mo period. Fig. 6A shows that only animals receiving suppressor cells preactivated with anti-CD3 and rB7-2 did not continue to gain weight. One animal from this same group was euthanized before the end of the study due to extensive weight loss and external signs of enteritis (data not shown). Although inflammation of the colon can be achieved with T cell adoptive transfer into immunodeficient hosts, we observed the greatest amount of inflammation in the small intestine, with the highest level of disease in the animals that received suppressor cells activated with anti-CD3 and rB7-2. Fig. 6B shows histopathology scores from different regions of the small intestine from each study group. Across all three sections of small intestine, the nTreg suppressor cells significantly limited inflammation compared with those activated with anti-CD3 and rB7-2, whereas the suppressor cells activated with anti-CD3, rB7-2, and rBTNL2 also limited inflammation in the duodenum and jejunum when compared with the same group.

With this T cell transfer model it is also possible to track the number of effector and suppressor cells in different immune compartments to assess the suppressor cells’ ability to limit effector cell homeostatic expansion. Two months after T cell transfer, CD45.2+ effector T cell expansion was evaluated in spleen, peripheral lymph nodes (cervical and inguinal), and mesenteric lymph nodes. The highest number of CD45.2+ effector cells was recovered from animals receiving anti-CD3/rB7-2 suppressor cells (Fig. 6C). Effector T cell expansion was most efficiently limited by nTreg in all three compartments, and anti-CD3/rB7-2/rBTNL2 suppressor cells lowered the recovered number of effector cells compared with those activated with anti-CD3 and rB7-2. In the mesenteric lymph nodes, BTNL2-induced suppressor cells limited effector CD4 numbers with statistical significance, limiting effector numbers similar to nTreg. These data are consistent with the small intestine inflammation scores and demonstrate that BTNL2/B7/TGF-β-mediated Foxp3 induction can lead to suppressive CD4 T cells capable of limiting the expansion and effector functions of pathogenic T cells.

Discussion

Thymic selection of T cells results in a diverse repertoire of TCRs that is precisely tuned to detect the presence of foreign peptide sequences presented by self-MHC. If the novel peptide derives from a pathogenic infectious agent, it is incumbent on the responding T cell to translate such a stimulus into a vigorous proliferative response and differentiation program to generate a clonal population of effector T cells capable of combating the infection. To help activate such a response, T cells employ a second signal in the form of CD28, brought into close proximity to MHC/TCR interactions by its ligands, B7-1 or B7-2, present on the APC. CD28 activates several signaling molecules necessary for proliferation and differentiation, such as PI3K, Akt, NF-κB, and MAPK. In some cases, however, such responses may be deleterious to the host. For example, if the pathogen load is high or the infection is in a vital organ, an unchecked immune response may be fatal. In addition, proinflammatory responses by T cells encountering...
novel tissue-restricted self-Ags, food, benign environmental Ags, or Ags from commensal bacteria would also lead to undesirable tissue damage and pathology.

The importance in regulating the strength of TCR/CD28-activating stimuli is reflected by the large number of proteins that are capable of attenuating this pathway. These include the CTLA-4 and PD-1 coreceptors, as well as a growing list of B7-related ligands that suppress T cell function similar to PD-1 ligands, but whose receptors have yet to be identified. Furthermore, recent data suggest that the activities of these costimulatory molecules are more complex than originally imagined. For example, Butte et al. (37, 38) found an unexpected interaction between B7-1 and PD-L1. Two recent publications also identify PD-L1 as the first inhibitory ligand to directly support Foxp3 expression and Treg differentiation (15, 16).

In this study, we show that BTNL2, a previously described inhibitory ligand of the butyrophilin/B7 family, can also induce Foxp3 expression and drive iTreg formation. We observe a role for BTNL2 in tempering the B7 signal, resulting in reduced proliferation and decreased production of inflammatory cytokines. We show that BTNL2 inhibits Akt phosphorylation and preserves Foxo1 activity, which is normally not operative in B7-activated CD4 cells, and was recently reported to support Foxp3 expression (27). Consistent with these reports, we found that BTNL2

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**FIGURE 5.** BTNL2 induces a nTreg gene signature in CD4 T cells. CD25-depleted CD4 T cells were stimulated with anti-CD3 and rB7-2.Fc in the presence or absence of rBTNL2.Fc for 3 d in cultures supplemented with IL-2 and TGF-β. Each condition was stimulated and processed independently in duplicate. RNA was isolated and assessed for gene expression by Affymetrix cDNA arrays. (A) Data were analyzed for genes upregulated or downregulated in the presence of BTNL2, and selected genes characteristic of nTreg and TGF-β–induced iTreg are shown along with fold changes. (B) All genes regulated by BTNL2 (p < 0.01) were examined for enrichment of Gene Ontology annotations using FatiGO. (C) Chemokines and cytokines regulated by BTNL2.
synergizes with a limiting concentration of TGF-β to promote Foxp3 expression and a T cell differentiation program that shares several features with that of nTreg. Lastly, BTNL2-generated Foxp3+ cells were found to be suppressive in vivo, indicating that a sustainable Treg program was induced.

Reduced activity of Akt and its associated signaling complex mTOR has emerged as a central component of Treg development and function. Originally thought to be an important driver of T cell proliferation and metabolism, Akt/mTOR signaling was recently found to also be important for proinflammatory cytokine production, but not absolutely required for T cell proliferation (39). Consistent with this report, BTNL2 was found to reduce Akt signaling and cytokine production without impairing IL-2–induced proliferation. One potential mechanism by which BTNL2 may reduce Akt function is through Phlpp1, an Akt phosphatase recently found to be important for human and mouse Foxp3 expression (40). Phlpp1 is upregulated in mouse and human nTreg (35, 40), and we report in this work that BTNL2-induced iTreg also upregulate Phlpp1 (Fig. 5A). Identification of a putative BTNL2 receptor should allow for better understanding of how BTNL2 influences T cell differentiation.

An unexpected finding from analysis of BTNL2-affected transcription was a unique cytokine/chemokine expression profile, in which genes for several chemokines were upregulated, whereas genes for several cytokines were repressed (Fig. 5C). The chemokines expressed by BTNL2-induced iTreg are known to recruit multiple immune cell types, including T cells, B cells, NK cells, monocytes/macrophages, and dendritic cells. If this phenotype is
recapitulated in vivo following T cell encounter of cognate Ag in the context of BTLN2-expressing APC (e.g., in the small intestines), then one function for the newly generated iTreg might be to recruit immune cells to further evaluate the source of novel Ag while maintaining an immunosuppressive environment. Such processes may play an important role in establishing dominant tolerance to benign environmental Ags.

Originally shown to be an inhibitor of T cell activation, we have characterized BTLN2 as a modulator of T cell differentiation, joining PD-L1 as an inducer of Foxp3 expression and iTreg formation. The specific conditions responsible for iTreg formation are critical for controlling inflammation at mucosal sites (41), underscoring the important role such ligands may play in maintaining tolerance to environmental Ags. The continued refinement of our understanding of how the B7/butyrophilin family modulates T cell costimulation and induces different types of iTreg should enable the conceptualization of therapeutics that promote tolerance in autoimmune patients.

Acknowledgments
We thank Marty Timour, Dianna Crawford, Heidi Jessup, and Aagen Washington Protein Science for contributions to these experiments.

Disclosures
All authors are employees of Amgen.

References
Supplementary Figure Legends

Figure S1. BTNL2 inhibits anti-CD3 stimulated changes in gene expression and induces a Foxo transcription factor signature. Mouse CD4 T cells were stimulated with plate-bound anti-CD3 in the presence of either IgG or BTNL2.Fc for 0, 4 or 24 hours and assessed by Affymetrix array for changes in gene expression. Each condition was stimulated and processed independently in duplicate A) Gene expression after 24 hours in the presence of anti-CD3 was compared with the 24 hour timepoint in the absence of a stimulation to generate a ratio plot of upregulated (red) and downregulated (blue) genes with p < 0.01 in both the presence and absence of BTNL2.Fc. B) A list of genes upregulated with BTNL2 at 4 hours with a p value < 0.05 and a fold change > 1.3 underwent Transfac analysis in Biobase to identify promoter sequences that are overrepresented in the BTNL2 dataset. Matrices with a matched promoter p-value of < 0.005 are shown. These matrices were not observed with anti-CD3 only.

Figure S2. Depletion of CD25+ T cells does not change the levels of Foxp3 induction with anti-CD3/B7-2/BTNL2 stimulation. CD25-depleted CD4 cells were cultured for 5 days on the indicated stimulations supplemented with TGF-β and IL-2. Foxp3 percentages and cell numbers were generated after harvesting cells, enumerating on Vicell, and performing flow cytometry analysis by staining with CD4, CD25 and Foxp3 antibodies.

Figure S3. Control proteins which bind T cells and have similar molecular structure do not induce Foxp3 expression in CD4 cells. Purified CD4+CD25- T cells were stimulated with the indicated immobilized conditions. On day 4, T cells were harvested, counted, and characterized by flow cytometry. All culture conditions were supplemented with 0.1ng/ml TGF-beta and 10ng/ml IL-2. Shaded bars represent total, viable CD4+CD25+Foxp3+ cell numbers. The CD4+CD25+Foxp3+ cell percentage is shown numerically. Data shown are representative of two experiments.

Figure S4. Foxp3 induction in the presence of limiting TGF-beta is dependent on BTNL2 signal, and varying CD3/CD28 signal strength does not reverse this phenotype. Purified CD4+T cells were stimulated with the indicated immobilized conditions. On day 4, T cells were harvested, counted, and characterized by flow cytometry. All culture conditions were supplemented with
0.2ng/ml TGF-beta and 10ng/ml IL-2. Shaded bars represent total, viable CD4+CD25+Foxp3+ cell numbers. The CD4+CD25+Foxp3+ cell percentages from the same stimulations are shown numerically. Data shown are representative of two experiments.
Supplementary Figure S1

A
Genes changed (p<0.01) following aCD3 stimulation (24h)
Genes changed (p<0.01) following aCD3 + BTNL2.Fc stimulation (24h)

B
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Supplementary Figure S2

The graph shows the percentage of foxp3+cells and total cells harvested from different conditions:

- Starting cells: 1%
- aCD3 + IgG: 9%
- aCD3 + B7-2: 2%
- aCD3 + B7-2/BTNL2: 48%

The y-axis represents the number of cells harvested, ranging from $0 \times 10^6$ to $8 \times 10^6$. The x-axis lists the conditions.
Supplementary Figure S3

- aCD3 + rB7-2 + IgG: 8%
- aCD3 + rB7-2 + BTNl2: 34%
- aCD3 + rICAM: 1%
- aCD3 + rB7-2 + anti-CD132: 6%
Supplementary Figure S4

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