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Regulatory T Cells Enhance Mast Cell Production of IL-6 via Surface-Bound TGF-β

Kirthana Ganeshan* and Paul J. Bryce*†

Mast cell degranulation is a hallmark of allergic reactions, but mast cells can also produce many cytokines that modulate immunity. Recently, CD25+ regulatory T cells (Tregs) have been shown to inhibit mast cell degranulation and anaphylaxis, but their influence on cytokine production remained unknown. In this study, we show that, rather than inhibit, Tregs actually enhance mast cell production of IL-6. We demonstrate that, whereas inhibition of degranulation was OX40/OX40 ligand dependent, enhancement of IL-6 was due to TGF-β. Interestingly, our data demonstrate that the Treg-derived TGF-β was surface-bound, because the interaction was contact dependent, and no TGF-β was detectable in the supernatant. Soluble TGF-β1 alone was sufficient to enhance mast cell IL-6 production, and these supernatants were sufficient to promote Th17 skewing, but those from Treg-mast cell cultures were not, supporting this being surface-bound TGF-β from the Tregs. Interestingly, the augmentation of IL-6 production occurred basally or in response to innate stimuli (LPS or peptidoglycan), adaptive stimuli (IgE cross-linking by specific Ag), and cytokine activation (IL-33). We demonstrate that TGF-β led to enhanced transcription and de novo synthesis of IL-6 upon activation without affecting IL-6 storage or mRNA stability. In vivo, the adoptive transfer of Tregs inhibited mast cell-dependent anaphylaxis in a model of food allergy but promoted intestinal IL-6 and IL-17 production. Consequently, our findings establish that Tregs can exert divergent influences upon mast cells, inhibiting degranulation via OX40/OX40 ligand interactions while promoting IL-6 via TGF-β. The Journal of Immunology, 2012, 188: 594–603.

Best known for their effector functions in allergic and autoimmune inflammation, mast cells have the capacity to produce a plethora of mediators involved in both innate and adaptive immunity (1–3). Of interest to us, mast cells have the capacity to generate a wide variety of cytokines, and the specific profile of cytokines generated by mast cells during an immune response can shape the nature of the ongoing inflammatory response. For example, mast cell-derived IL-10 has been shown to limit skin inflammation during contact dermatitis (4), whereas response. For example, mast cell-derived IL-10 has been shown to limit skin inflammation during contact dermatitis (4), whereas conversely, mast cell-derived TNF promotes Ag-mediated airway inflammation and enhances T cell activation (5, 6). Recently, IL-6 has been described as an important early cytokine produced by mast cells because mast cell-derived IL-6 was shown to be necessary for bacterial clearance and host survival in a mouse model of Klebsiella pneumoniae infection (7). Cytokine production by mast cells can also occur independent of the degranulation response (8–10). However, the mechanisms that control the release of selective mediators from mast cells are unknown.

Natural regulatory T cells (Tregs) make up 5–10% of the naive peripheral CD4+ T cell population and play critical roles in the maintenance of tolerance and resolution of inflammation (11). Tregs can exert their suppressive effects by a diverse array of mechanisms that include directly engaging other immune cells via a number of cell-surface receptors (e.g., GITR, CTLA-4, and OX40), as well as through the release of cytokines IL-10, IL-35, and TGF-β (12). Although they are best recognized for their ability to mediate Ag-specific suppression of immune responses, recent evidence has shown that Tregs exert influences that are Ag independent, such as infectious tolerance (13). In this study, Tregs cause naive T cells to develop into new Tregs, allowing for an increased suppressive environment and expanded immunological repertoire of tolerance. This function of Tregs is dependent on cell surface-bound TGF-β (14), establishing that TGF-β bound to the surface of Tregs possesses biological activity.

Tregs have recently been shown to be one way that mast cell release of mediators is controlled. Mast cell degranulation upon stimulation by IgE/Ag-mediated activation is suppressed by coculture with Tregs, and in vivo depletion of Tregs enhanced mast cell-dependent anaphylactic responses (15). Although mast cells and Tregs possess a number of potential interaction partners, this suppression of degranulation required OX40/OX40 ligand (OX40L) interactions. Mast cells and Tregs exhibit substantial colocalization in tissues and lymph nodes (15, 16), and Tregs also recruit mast cells into tissues. For example, Tregs promote mast cell progenitor recruitment to the lung during allergic inflammation (17), whereas Treg-derived IL-9 promotes recruitment of mast cells into transplanted allografts, important for maintaining allograft tolerance (18). Therefore, mast cell/Treg interactions are likely to be occurring during homeostasis as well as during the course of an inflammatory response. However, the influence of Tregs on mast cell production of cytokines has not been investigated.
In this study, we confirm that coculture of Tregs with mast cells suppresses degranulation, but show that this actually enhances the levels of IL-6 being produced from the mast cell. Mechanistically, this is contact dependent and but independent of the OX40/OX40L-dependent inhibitory effects of Tregs on mast cell degranulation. Instead, enhancement of IL-6 is dependent on surface-bound TGF-β and is driven by enhancing the de novo generation of IL-6 upon mast cell stimulation. Using a model of food allergy, we demonstrate that the adoptive transfer of Tregs into sensitized mice prevents mast cell-dependent anaphylaxis upon food challenge. Concomitantly, mice that received Tregs exhibited significantly enhanced IL-6 and IL-17 levels in the intestinal tissue. Consequently, our data demonstrate that Tregs possess an unappreciated capacity to enhance proinflammatory cytokines from mast cells while simultaneously suppressing their degranulation. Importantly, our findings establish that these events occur via divergent mechanisms.

Materials and Methods

Mice

C57BL/6 and BALB/c mice were purchased from Taconic Farms (Bridgeport, CT), IL-6-/- mice were purchased from The Jackson Laboratory (Bar Harbor, ME). Foxp3-GFP mice were bred and housed under specific pathogen-free conditions at Northwester University. All experiments were approved by the Northwestern University Animal Care and Use Committee.

Bone marrow-derived mast cell differentiation

Bone marrow was isolated from the femurs of female, age-matched C57BL/6 and IL-6-/- mice and cultured in complete media (RPMI 1640 with 2 mM l-glutamine, 10% FCS, 100 U/ml penicillin, 100 μg/ml streptomycin, 1% nonessential amino acids, 1 mM sodium pyruvate, 10 mM HEPES, and 0.05 mM 2-ME) containing 30 ng/ml rIL-3 (R&D Systems). After 4 wk, bone marrow-derived mast cells (BMMCs) were analyzed for surface expression of FceRI and c-Kit by flow cytometry. Cultures of >95% FceRI+ and c-Kit+ BMMCs were used.

Isolation of CD4+CD25+ and CD4+CD25- T cells

CD4+CD25- T cells were isolated from pooled spleen and lymph nodes of naive C57BL/6 mice using CD4+CD25- isolation kit (Miltenyi Biotec) following the manufacturer’s instructions. Twenty-four–well plates were coated with anti-hamster IgG (Jackson ImmunoResearch Laboratories) at 3 μg/ml. Following incubation, plates were washed with PBS, and naive T cells were plated at 5 × 10⁶ cells/ml. A total of 500 μl BMMC supernatant from cultures of BMMCs alone, BMMC–TGF–β, and BMMC–Treg, in which BMMCs were activated through IgE/Ag cross-linking, was added to naive T cells with 500 μl fresh media. Soluble anti-CD3ε and anti-CD28 were added at 0.2 μg/ml for T cell stimulation. As a positive control for Th17 generation, naive T cells were cultured under the following conditions: 20 ng/ml IL-6, 2 ng/ml rTGF-β, 5 μg/ml anti-IL-4, and 5 μg/ml anti-IFN-γ with anti-CD3 and anti-CD28. Untreated samples received only anti-CD3ε and anti-CD28 stimulation. Cells were cultured for 3 d, and then restimulated with PMA/ionomycin in the presence of monensin (GolgiStop; BD Biosciences) for 4 h. All samples were stained for intracellular IL-17 and analyzed by flow cytometry.

Histamine and cytokine/chemokine analysis

Histamine enzyme immunoassay (BD Biosciences) was used to detect histamine in culture supernatants and was performed following the manufacturer’s instructions. IL-6 was detected in culture supernatants and cell lysates by sandwich ELISA (BD Biosciences). Mouse Inflammation CBA kit (BD Biosciences) was used to detect TNF, IFN-γ, IL-2, and MCP-1 in culture supernatants following the manufacturer’s instructions.

Real-time RT-PCR and mRNA stability assay

IgE-treated BMMCs were treated with rTGF-β for 24 h. Both untreated and treated BMMCs were stimulated with DNP-HSA for 2 h. For mRNA stability assays, actinomycin D (Sigma-Aldrich) was then added (5 μg/ml), and cells were collected at the time points indicated (Fig. 6D). Total RNA was isolated using Qiagen RNeasy kits (Qiagen). cDNA was synthesized using a qScript cDNA synthesis kit (Quanta). Gene expression was determined by PCR using an ABI 7500 Thermal Cycler (Applied Biosystems) and specific TaqMan probes (Applied Biosystems) for each gene of interest. Expression of β-actin was used as a housekeeping gene for analysis of changes in the cycle threshold values. The fold induction above BMMCs alone was determined based on changes in the 8 cycle threshold values.

Flow cytometry

For staining of cell-surface TGF-β, isolated CD4+CD25- T cells were stimulated for 24 h with CD3/CD28 stimulation. Samples were blocked with anti-CD16/CD32 for 15 min at 4°C before being incubated with unconjugated chicken anti–TGF-β or chicken IgY (R&D Systems) at 1 μg/10⁶ cells for 20 min. After washing, allopurinol-conjugated anti-chicken IgY (Jackson ImmunoResearch Laboratories) was added for 20 min and then washed three times before analysis. Samples were gated on CD4+ cells and analyzed using FlowJo software (Tree Star). For intracellular IL-17 staining, PE anti–IL-17 (BD Biosciences) or isotype control was used with BD Biosciences intracellular staining buffer set according to the manufacturer’s instructions (BD Biosciences).
**Experimental food allergy model**

Mice (BALB/C, 4–6 wk old, maintained on an OVA-free diet) were sensitized as previously described (19). Briefly, mice received 100 µg OVA with 20 µg SEB adjuvant via a ball-ended mouse-feeding needle once per week for 8 wk. Sensitization was confirmed by serum OVA-specific IgE analysis, as previously described (19). At week 9, sensitized mice received 0.5 × 10⁶ Tregs or CD25⁻ T cells (isolated from the spleen and mesenteric lymph nodes of naive BALB/C mice) i.v. via retro-orbital injection. Twenty-four hours later, all mice were challenged with an oral administration of 5 mg OVA. Symptom scoring was performed every 15 min for 1 h in a blinded fashion by two independent investigators according to previously described parameters of symptoms for determining IgE-mediated responses in mouse models of food allergy (20). Concurrently, airway obstruction responses, as determined by changes in the enhanced pause (Penh) response, were measured using whole-body plethysmography (BUXCO, Troy, NY). Serum mast cell protease-1 (MCPT-1) levels were assessed by sandwich MCPT-1 ELISA following the manufacturer’s instructions (BD Biosciences).

**Intestinal cytokine analysis**

Intestinal tissue was homogenized in ice-cold PBS containing protease inhibitor mixture (Sigma-Aldrich). Samples were centrifuged at 12,000 × g for 7 min. Supernatants were removed and analyzed for IL-6 and IL-17 by ELISA. Total protein concentration of supernatants was determined by bicinchoninic acid (Pierce).

**Statistical analysis**

Results are expressed as the means ± SEM. Data was analyzed using a nonpaired Student t test (GraphPad Prism; GraphPad). A p value <0.05 was considered significant. The p values >0.05 were not considered significant.

**Results**

**Tregs enhance mast cell cell-derived IL-6 in a cell–cell contact-dependent manner**

Initially, we investigated the influence of T cells on Ag-stimulated responses by IgE-sensitized BMMCs. BMMCs pretreated with anti-DNP IgE were cultured with Tregs or CD4⁺CD25⁻ T cells and activated by addition of DNP-HSA. In the presence of Tregs, BMMCs degranulation was significantly reduced, as previously described (15) (Fig. 1A). We then analyzed cytokine production by ELISA. BMMC-CD4⁺CD25⁻ T cell cultures had significantly increased levels of IFN-γ (Fig. 1B) and IL-2 (Fig. 1C) as compared with cultures of BMMC-Tregs or BMMC alone, demonstrating that mast cells alter T cell cytokine production, as previously suggested (6). Of the cytokines we investigated, IL-6 was unique in that it was significantly increased in BMMC-Treg cultures only (Fig. 1D), whereas cultures from BMMC with either T cell population demonstrated increased TNF (Fig. 1E), and MCP-1 was unaltered by coculture (Fig. 1F). Independent experiments using CD4⁺/GFP⁺ cells derived from the Foxp3/GFP knockin that were sorted using a MoFlo high-speed cell sorter (DakoCytometry) demonstrated similar enhanced IL-6 (data not shown).

Because IL-6 can be generated by both mast cells and T cells, we used IL-6⁻/⁻ cells to identify the source. Wild-type (C57BL/6) and IL-6⁻/⁻ BMMCs were generated and cocultured with Tregs from wild-type or IL-6⁻/⁻ mice. As shown in Fig. 2A, wild-type BMMCs with IL-6⁻/⁻ Tregs showed enhanced IL-6 production, whereas no IL-6 was produced in cultures of IL-6⁻/⁻ BMMCs with wild-type Tregs. This demonstrates that mast cells are the source of IL-6. Furthermore, the enhanced IL-6 production from wild-type BMMCs was observed with either wild-type or IL-6⁻/⁻ Tregs, suggesting Treg-derived IL-6 is not required.

To determine if this was cell–cell contact or soluble mediator dependent, the cells were cultured using a Transwell system (Costar; Corning), in which cell–cell contact was inhibited but free exchange of soluble mediators persists. Fig. 2B demonstrates a requirement for cell–cell contact because separation of the Tregs from BMMCs prevented the enhanced IL-6 production.

**Tregs enhance mast cell production of IL-6 to various stimuli**

During these experiments, we provided both Treg activation using CD3/CD28 beads and mast cell activation via IgE/Ago. We next sought to investigate the requirements for activation on the IL-6 response. IL-6 production was increased in BMMC-Treg cultures either without or with T cell stimulation (CD3/CD28) (Fig. 3A, 3B). Furthermore, whereas IgE-mediated mast cell activation with Ag (DNP-HSA) did enhance the levels of IL-6 (Fig. 3B), Tregs were capable of elevating IL-6 even in the absence of BMMC stimulation (no DNP-HSA) (Fig. 3A). Mast cells have been shown express MHC II and present peptide to Tregs (21), and so, to exclude any potential role of cognate MHC II interactions with TCR, BMMCs were pretreated with a blocking anti-MHC II Ab prior to coculture with Tregs. This had no effect on the increased IL-6 production (Supplemental Fig. 1). Together, these data demonstrate that the ability of Tregs to enhance mast cell production of IL-6 is unlikely to be dependent on TCR/MHC II interactions or mast cell activation and instead is due to an interaction that is independent of Ag-specific requirements.

We next investigated if Tregs could also influence mast cell IL-6 production in response to innate inflammatory stimuli. BMMC-Treg cultures were stimulated with PGN or LPS to trigger TLR2 or TLR4, respectively. As Fig. 3C demonstrates, Tregs significantly enhance production of IL-6 in response to both PGN and LPS. Furthermore, BMMC activation with IL-33, a recently described cytokine that potently stimulates mast cells (22), results in enhanced IL-6 production in BMMC-Treg cultures. Together, these data suggest that an innate function of Tregs actively primes mast cells for IL-6 production when the mast cell is triggered by either adaptive or innate stimuli.

**Tregs suppress degranulation and enhance IL-6 via different mechanisms**

As demonstrated in Fig. 2B, Treg priming of mast cells occurred via a cell–cell contact-dependent mechanism. To identify the interaction mediating this response, we began by investigating the OX40/OX40L interaction described to mediate Treg suppression of mast cell degranulation (15). BMMCs were pretreated with a blocking anti-OX40L Ab prior to culture with Tregs. Surprisingly, there was no effect of blocking the OX40/OX40L interaction on the enhanced IL-6 production (Fig. 4A) despite clear abrogation of the Treg suppression of degranulation (Fig. 4B). Blocking Abs to PDL1, ICOS ligand, and GITR were also investigated, with no significant effect on the enhanced IL-6 production from mast cells (Supplemental Fig. 2).

Whereas surface-bound TGF-β has been established as a mechanism through which Tregs can suppress immune responses (14, 23, 24), some investigators have reported being unable to detect TGF-β on the surface of Tregs (25). We were able to detect TGF-β on the surface of our isolated Tregs by flow cytometry (Fig. 4C), whereas soluble TGF-β in the supernatant was undetectable. Addition of anti–TGF-β blocking Ab to the cocultures significantly impaired the enhanced IL-6 production, as compared with isotype control-treated cultures (Fig. 4D). This inhibition was also seen using a different anti–TGF-β Ab clone (Fig. 4E). However, blocking the TGF-β pathway had no effect on degranulation responses, and the Tregs were still able to suppress mast cell histamine release (Fig. 4F). As such, our data suggest that Tregs use two distinct mechanisms to regulate mast cells: degranulation...
is inhibited by OX40/OX40L interactions, whereas the TGF-β/TGF-βR interaction is necessary for the positive effect on IL-6 production we describe in this study. Soluble TGF-β has been previously shown to inhibit mast cell growth and activation (26–28). However, the effects on mast cell-derived cytokines have not been reported. We therefore investigated if TGF-β (rTGF-β) would be sufficient to enhance IL-6. IgE-sensitized BMMCs were treated with rTGF-β for 24 h. Treated BMMCs were then stimulated with Ag (DNP-HSA). rTGF-β dose dependently increased mast cell production of IL-6 but only upon IgE/Ag stimulation (Fig. 5A). Furthermore, treatment with rTGF-β did not affect IgE/Ag-triggered degranulation, because there was no change in histamine release between untreated and rTGF-β-treated BMMCs (Fig. 5B). These findings further support the concept of independent mechanisms that enhance mast cell IL-6 production versus degranulation.

**TGF-β is sufficient to enhance mast cell-derived IL-6**

We investigated the mechanism by which IL-6 production is enhanced in mast cells. Mast cell granules are capable of storing a variety of mediators, including cytokines (29), and so we initially explored if TGF-β might increase the storage of IL-6 protein. Cell lysates from rTGF-β–treated BMMCs showed no difference in total IL-6 levels in either unstimulated or stimulated BMMCs (Fig. 6A), suggesting no influence on IL-6 storage. Treatment with cycloheximide to block de novo protein synthesis prior to stimulation also demonstrated a requirement for stimulation-induced synthesis (Fig. 6B). Therefore, we next ascertained the impact on IL-6 gene expression. Treatment with rTGF-β significantly increased IL-6 gene expression as compared with untreated BMMCs (Fig. 6C). rTGF-β–treated BMMCs also exhibited increased mcpt1 (mast cell chymase) and decreased fcRIa gene expression, as has been previously reported (Supplemental Fig. 3) (26, 30). This increase in IL-6 gene expression was not due to increased mRNA stability because IL-6 mRNA decayed at the same rate in both rTGF-β–treated and untreated samples (Fig. 6D) and supports the elevated IL-6 being due to increased gene transcription. We next tested these findings in the mast cell-Treg coculture system. Wild-type BMMCs were cultured with T cells derived from IL-6−/− mice, which do not generate IL-6 mRNA. Gene expression analysis...
demonstrated significantly increased IL-6 gene expression in BMMCs cocultured with Tregs (Fig. 6) versus CD25^+ T cells or BMMCs alone. These studies demonstrate that TGF-β and Tregs exert their influence by increasing IL-6 gene expression in mast cells that promotes elevated de novo cytokine synthesis and release of IL-6.

Mast cell-derived IL-6 is sufficient to promote conversion to Th17

Despite previous reports suggesting that mast cells might promote naive T cell conversion to Th17 (16, 31), the cellular sources of IL-6 for Th17 differentiation have remained unclear. We asked if Treg/TGF-β-induced mast cell-derived IL-6 was sufficient to promote Th17 differentiation in vitro. Supernatants from cultures of BMMC alone, BMMC–TGF-β, and BMMC-Treg, in which BMMCs were activated with IgE/Ag, were used to condition naive CD4^+CD62L^+ T cells. Both BMMC–TGF-β and BMMC-Treg culture supernatants were analyzed for IL-6 production, which were significantly increased as compared with BMMC alone (data not shown). Untreated naive T cells were negative for IL-17 production, whereas cells conditioned under Th17-skewing con-
ditions (IL-6 + TGF-β) were IL-17 positive (Fig. 7). Interestingly, naive T cells conditioned with supernatants from BMMC–TGF-β cultures had significantly increased proportions of IL-17–positive cells, despite no exogenous IL-6 being added. In contrast, BMMC–Treg supernatants, in which there was no detectable soluble TGF-β (data not shown), did not promote Th17 development. Thus, our data demonstrate that the IL-6 promoted by TGF-β from mast cells is functional and sufficient to promote Th17 skewing in vitro but that soluble TGF-β is required. This does not occur when the IL-6 is driven by contact with Tregs in vitro.

Adoptive transfer of Tregs into food-allergic mice prevents anaphylaxis and promotes intestinal IL-6 production

Using a mouse model of food allergy we described, whereby mice exposed to OVA plus SEB adjuvant (SEBOVA) exhibit intestinal mastocytosis, elevated Ag-specific IgE, and anaphylaxis upon oral challenge (19), we had previously demonstrated a reduced expression of both TGF-β and Foxp3 in the intestine of mice as compared with controls. Therefore, we examined the expression of IL-6 and IL-17 in this model also. As shown in Fig. 8A and 8B, gene expression for both IL-6 and IL-17 were significantly reduced in anaphylactic SEBOVA mice.

We next examined whether the adoptive transfer of Tregs into sensitized mice would alter either of these responses. Using a similar approach to Gri et al. (15), who demonstrated inhibition of passive anaphylaxis by Treg transfer, 0.5 × 10^6 Tregs or CD25− T cells were isolated from naive BALB/C mice and i.v. transferred into fully sensitized SEBOVA mice 24 h prior to oral challenge. As depicted in Fig. 8C, all SEBOVA mice exhibited significantly elevated serum levels of OVA-specific IgE, demonstrating that the T cell transfer had no influence on sensitization. However, upon oral challenge with OVA, the anaphylactic response observed in SEBOVA mice was absent in five of the eight SEBOVA mice that received Tregs but persisted in those that re-
that cytokine production is also affected but rather than suppress, Tregs actually promote mast cell production of IL-6.

Foxp3+ Tregs possess an arsenal of methods through which they have been shown to inhibit inflammation and immunity, including release of soluble factors, such as IL-10, IL-35, and TGF-β, as well as contact-dependent mechanisms, such as OX40 interacting with OX40L (12). This OX40/OX40L mechanism was previously shown to mediate Treg inhibition of in vitro mast cell degranulation, whereas depletion of Tregs was sufficient to enhance anaphylaxis in vivo (15), suggesting that Tregs constitutively inhibit mast cell degranulation. Our data suggest that this is only one mechanism through which mast cells and Tregs interact and that surface TGF-β on Tregs can alter mast cell cytokine production.

In addition to its secretion, recent studies have shown TGF-β can be expressed on the cell surface of activated Tregs in a complex with latency-associated peptide and GARP (32). Functionally, disruption of this complex reduces the capacity of Tregs to suppress T cell proliferation or induce differentiation of new Tregs during the process of infectious tolerance (14, 32). As a result, the functions of surface-bound TGF-β have been generally seen as inhibitory in nature. Although previous studies have established that soluble TGF-β can alter the expression of mast cell proteases and FcεRI (26), we were unable to detect soluble TGF-β in supernatants from our mast cell-Treg coculture experiments and so we examined the Tregs used for their surface expression. Our data show cell-surface expression of TGF-β and that Ab blockade was sufficient to prevent the enhancing effects of Tregs on mast cell production of IL-6 in our cocultures. Therefore, we conclude that Tregs mediate their influence on mast cells via a contact-dependent, surface-bound TGF-β mechanism and that this is a mechanism that Treg possess to exert positive, stimulatory influences over other cells.

In considering the mechanisms through which IL-6 may be enhanced, we define that the enhancing influence of TGF-β was at the level of enhanced gene transcription, rather than mRNA stability or increased protein storage. TGF-β receptor activation can engage both Smad-dependent and -independent signaling pathways (33). In human bronchial epithelial cells and prostate cancer cells, TGF-β activation has been shown to promote IL-6 gene expression through Smad-dependent pathways (34, 35). In this study, Smad proteins can couple with other IL-6–associated transcription factors (e.g., c-Jun/AP-1 and NF-kB) to drive IL-6 gene transcription. Smad3 was shown to directly act with c-Jun/c-Fos components to mediate TGF-β–stimulated transcription (36), suggesting this might be a pathway through which TGF-β could influence IL-6 transcription. Preliminary studies aimed at investigating the requirement for Smad3 in our responses have yielded contradictory results, with pharmacological inhibition using a Smad3 inhibitor reducing the IL-6 levels but no apparent difference in BMMC derived from Smad3+/− mice (data not shown). We are continuing to investigate this further. However, TNFR-associated factor 6, which is a Smad-independent TGF-β–activated factor (37), has also been shown to regulate IL-6 production in mast cells (38) and B cells (39). Consequently, the specific mechanisms through which TGF-β, via Treg presentation, might promote IL-6 production are an exciting topic for future studies but may theoretically occur via either of the described major pathways from the TGF-β receptors.

One intriguing component of our study is that, despite both cells having critical roles in adaptive immunity, mast cells and Tregs clearly cooperate via mechanisms that are not Ag specific. Mast cells and Tregs have been demonstrated to reside in close proximity to one another in secondary lymphoid tissues as well as in mucosal tissues during homeostasis (15, 40), suggesting that these inter-

**FIGURE 7.** Mast cell-derived IL-6 is sufficient to skew naive T cells to Th17. Naive T cells (CD4+CD62L+) were placed under untreated or Th17-skewing conditions (IL-6 + TGF-β). BMMCs, BMMC + rTGF-β, or BMMC + CD25+ cultures were stimulated with DNP-HSA and supernatants collected. Supernatants were then used to treat naive T cells. Cells were collected at day 3 and analyzed for IL-17 production by intracellular flow cytometry. A, Representative flow plots depicted. B, Quantification of flow cytometry plots (n = 5). ***p < 0.001.
actions likely occur in the absence of inflammation and Ag-specific requirements. Mast cell-derived IL-6 has been shown to be important in a diverse range of immune contexts, including driving B cell activation and IgA secretion (41), limiting tumor growth (42) and providing protection against *Klebsiella pneumonia* (7). We anticipate that Tregs and TGF-β would also likely regulate such responses.

Functionally, our data demonstrate that mast cells are a potential source of IL-6 for Th17 differentiation and that this is regulated by Tregs. This supports a recently published study showing mast cells can promote Treg and naive T cell differentiation to Th17 in vitro (16) but contrasts with their conclusions that proposed mast cells functioned to promote IL-6 production from the naive T cells. Our coculture experiments using mast cells or T cells from IL-6−/− mice conclusively demonstrated that the mast cell is the critical source of IL-6 production in our studies. Our data would also suggest that Tregs or mast cells alone are not capable of supplying sufficient soluble TGF-β to drive Th17 differentiation because activated BMMC supernatants or BMMC-Treg culture supernatants were not able to induce IL-17 production. However, it remains to be determined if Tregs might use surface-bound TGF-β to both drive IL-6 production from mast cells and also provide TGF-β–dependent signals to naive T cells concurrently or whether an alternative source of TGF-β would be required. Furthermore,

**FIGURE 8.** Adoptive transfer of Tregs inhibits anaphylaxis and promotes intestinal IL-6 production. Mice were treated with OVA alone or SEBOVA. Twenty-four hours after challenge, the expression of IL-6 (A) and IL-17 (B) from cells in the mesenteric lymph nodes was determined. Following the same sensitization protocol, control-treated or mice sensitized to OVA (SEBOVA) received Tregs (CD25+) or CD25− T cells 24 h before oral Ag challenge. C, Serum levels of OVA-specific IgE were measured to determine effective sensitization. D, Forty-five minutes postchallenge, anaphylactic symptom scores were assigned. E, Airway obstruction responses were measured using whole-body plethysmography. Data represent mean Penh value during each 5-min period. F, Serum MCPT-1 levels were measured by ELISA. IL-6 (G) and IL-17 (H) protein levels were determined by ELISA 24 h postchallenge in supernatants from intestinal tissue homogenates. Data are mean ± SEM from two independent experiments (*n* = 5–8). *p < 0.05, **p < 0.01, ***p < 0.001.
Tada et al. (43) previously demonstrated that rTGF-β inhibited IL-6 production from macrophages but enhanced production from Langerhans cells upon activation, raising the possibility of different cell types possessing differential potential for IL-6 production via this mechanism. Also, in contrast to our findings in this paper, coculture of islet cells for 2 d with Tregs was shown to reduce IL-6 mRNA levels (44). Consequently, it is intriguing to postulate a scenario whereby Tregs might inhibit IL-6 from cells in one tissue compartment but actively enhance those in another.

Using in vitro approaches and a passive anaphylaxis model, Tregs have previously been demonstrated to inhibit mast cell degranulation (15). In this study, we demonstrate that the Tregs also inhibit active anaphylaxis, because SEBOVA mice that received Tregs exhibited reduced symptom scores, an absence of airway obstruction responses, and significantly reduced serum MCPT-1 levels in a model of food allergy. This demonstrates that Tregs possess the potential to prevent anaphylactoid responses despite the presence of Ag-specific IgE and dominant Th2-skewed immunity. Clinically, it is well described that the majority of individuals who possess food Ag-specific IgE show no clinical reactivity (45). This nonresponder tolerance might be due to postulate a scenario whereby Tregs might inhibit IL-6 from providing an alternative path to regulatory mechanisms for anaphylaxis.

References


Disclosures

The authors have no financial conflicts of interest.


