Resolution of airway inflammation and hyperreactivity after in vivo transfer of CD4⁺CD25⁺ regulatory T cells is interleukin 10 dependent

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Deficient suppression of T cell responses to allergen by CD4⁺CD25⁺ regulatory T cells has been observed in patients with allergic disease. Our current experiments used a mouse model of airway inflammation to examine the suppressive activity of allergen–specific CD4⁺CD25⁺ T cells in vivo. Transfer of ovalbumin (OVA) peptide–specific CD4⁺CD25⁺ T cells to OVA–sensitized mice reduced airway hyperreactivity (AHR), recruitment of eosinophils, and T helper type 2 (Th2) cytokine expression in the lung after allergen challenge. This suppression was dependent on interleukin (IL) 10 because increased lung expression of IL-10 was detected after transfer of CD4⁺CD25⁺ T cells, and regulation was reversed by anti–IL-10R antibody. However, suppression of AHR, airway inflammation, and increased expression of IL-10 were still observed when CD4⁺CD25⁺ T cells from IL-10 gene–deficient mice were transferred. Intracellular cytokine staining confirmed that transfer of CD4⁺CD25⁺ T cells induced IL-10 expression in recipient CD4⁺ T cells, but no increase in IL-10 expression was detected in airway macrophages, dendritic cells, or B cells. These data suggest that CD4⁺CD25⁺ T cells can suppress the Th2 cell–driven response to allergen in vivo by an IL-10–dependent mechanism but that IL-10 production by the regulatory T cells themselves is not required for such suppression.
CD4+CD25+ regulatory T cells suppress AHR and leukocyte recruitment in vivo

AHR is characteristic of the pulmonary response to inhaled antigen in sensitized animals. Transfer of CD4+CD25+ regulatory T cells significantly decreased AHR in OVA-sensitized mice at a dose of 30 mg/ml methacholine (P < 0.05; Fig. 1 A).

Figure 1. OVA-specific CD4+CD25+ regulatory T cells regulate allergen-induced airway inflammation in vivo. OVA-sensitized mice received either 5 x 10^5 CD4+CD25+ cells or an equivalent volume of PBS and were challenged through the airways with OVA. (A) AHR was measured 24 h after the final OVA challenge using a Buxco system in which mice were exposed to increasing concentrations of methacholine. Values are expressed as means ± SEM (n = 9–12 mice/group from two separate experiments). *, P < 0.05 compared with OVA-sensitized mice that received PBS instead of CD4+CD25+ cells. (B) Lungs were fixed, sectioned, and stained with hemotoxylin and eosin. Representative sections are shown for each treatment group. BAL and lung tissue digest cells (C) were isolated as described in Materials and methods, and eosinophil numbers were determined by differential counts. Values are expressed as medians (n = 9–12 mice/group from two separate experiments). *, P < 0.05 compared with OVA-sensitized mice that received PBS instead of CD4+CD25+ cells.
These results were confirmed by direct measurement of lung resistance (RL) and dynamic compliance (Cdyn; Fig. S3, available at http://www.jem.org/cgi/content/full/jem.20051166/DC1). In contrast, transfer of OVA-specific CD4+CD25+ regulatory T cells had no effect on increased AHR after allergen challenge (unpublished data).

Transfer of CD4+CD25+ regulatory T cells also significantly reduced eosinophil numbers in the airway lumen (BAL cells) and lung parenchyma of OVA-sensitized and -challenged mice (P < 0.05; Fig. 1, B and C). In contrast, transfer of CD4+CD25+ T cells had no such effect on leukocyte recruitment to the airway lumen after allergen challenge (unpublished data).

**Th2 response to allergen challenge is modulated by transfer of CD4+CD25+ regulatory T cells**

Th2 cells are important effector cells in the pulmonary allergic response, and, therefore, differences in Th2 cell numbers could potentially account for the decreases in AHR and eosinophilia mediated by transfer of CD4+CD25+ regulatory T cells. Th2 cell numbers were determined in the BAL and lung tissue by co-staining cells with CD4 and the Th2 cell–specific marker T1/ST2. There was an increase in Th2 (CD4+T1/ST2+) cell numbers in the airway lumen and lung of OVA-sensitized and -challenged mice compared with unsensitized mice 24 h after the final OVA challenge, and this was significantly reduced by transfer of CD4+CD25+ regulatory T cells (P < 0.05; Fig. 2, A and B). Furthermore, antigen-induced increases in BAL IL-5 and IL-13 were significantly reduced by transfer of CD4+CD25+ regulatory T cells in OVA-sensitized mice (P < 0.05; Fig. 2 C). Similarly, lung homogenate IL-5 and IL-13 were also decreased by transfer of CD4+CD25+ regulatory T cells (Fig. 2 D). In contrast, production of the Th1-specific cytokine IFN-γ was unaffected by transfer of CD4+CD25+ regulatory T cells. Lung IFN-γ levels were increased in OVA-sensitized mice to 843 ± 94 pg/ml from 620 ± 53 pg/ml in alum controls. However, there was no substantial difference between OVA-sensitized mice and mice that received CD4+CD25+ cells (838 ± 106 pg/ml).

The chemokines eotaxin/CCL11, MDC/CCL22, and TARC/CCL17 are thought to be involved in leukocyte recruitment during an allergic response and in particular for the recruitment of eosinophils and Th2 cells (14). By decreasing production of these chemokines, regulatory T cells could potentially suppress the Th2 response. However, BAL and lung levels of eotaxin/CCL11, MDC/CCL22, and TARC/CCL17 were unaffected by transfer of CD4+CD25+ regulatory T cells (Fig. S4, available at http://www.jem.org/cgi/content/full/jem.20051166/DC1, and not depicted).

Similarly, transfer of CD4+CD25+ T regulatory cells had no effect on serum IgE or OVA-specific IgE levels in OVA-sensitized mice (Fig. S5, available at http://www.jem.org/cgi/content/full/jem.20051166/DC1).

**CD4+CD25+ T cell transfer increases pulmonary IL-10 expression**

The regulatory activity of CD4+CD25+ T cells has been attributed to IL-10 and TGF-β in some models (6, 7, 8). Therefore, these cytokines were measured in BAL fluid and lung homogenate supernatant 24 h after the final allergen challenge. The concentration of IL-10 was significantly increased in the BAL and lung of OVA-sensitized mice that received CD4+CD25+ regulatory T cells compared with OVA-sensitized mice that received PBS (P < 0.05; Fig. 2, E and F). In contrast, levels of TGF-β were unaffected by transfer of CD4+CD25+ regulatory T cells (Fig. 2, E and F).

**Suppression of allergic inflammation and AHR by CD4+CD25+ regulatory T cells is IL-10 dependent**

Because suppression of Th2 responses after transfer of OVA-specific CD4+CD25+ T cells in OVA-sensitized mice was...
associated with increased expression of IL-10, we investigated the role of IL-10 in regulation. To this end, we administered a neutralizing antibody against the IL-10 receptor during the allergen challenge phase. Anti–IL-10R treatment completely abrogated the suppression of AHR and lung eosinophil infiltration by CD4⁺CD25⁺ regulatory cells (Fig. 3, A and B). Moreover, CD4⁺CD25⁺ regulatory T cells were unable to reduce Th2 cell numbers and IL-5 and IL-13 levels in the lung in the presence of anti–IL-10R (Fig. 3, C and D, and not depicted). Interestingly, anti–IL-10R treatment had no effect on the increased lung IL-10 levels associated with CD4⁺CD25⁺ regulatory T cells (Fig. 3 E).

Modulation of allergic inflammation and AHR is not dependent on CD4⁺CD25⁺ T cell–derived IL-10

Because we had demonstrated that the inhibition of allergen-induced airway inflammation by CD4⁺CD25⁺ regulatory T cells was IL-10 dependent, we investigated whether production of IL-10 from the regulatory T cells themselves was necessary for their suppressive activity. We therefore derived CD4⁺CD25⁺ T cells from IL-10⁻/⁻ DO11.10 animals and transferred them during allergic airway disease. AHR, eosinophil recruitment, and Th2 cytokine expression were suppressed after transfer of CD4⁺CD25⁺ regulatory T cells derived from either wild-type or IL-10–deficient mice (Fig. 4, A–D). Interestingly, transfer of CD4⁺CD25⁺ regulatory T cells from IL-10 knockout mice still resulted in increased expression of IL-10 in the lung tissue of allergen-challenged mice (Fig. 4 E).

IL-10 production from CD4⁺ T cells is increased by transfer of CD4⁺CD25⁺ regulatory T cells

Because we had established that IL-10 production from the CD4⁺CD25⁺ regulatory T cells was not necessary for their suppressive activity, we sought to determine the source of

Figure 3. Suppression of allergen-induced airway inflammation is IL-10 dependent. Mice were treated with anti–IL-10R antibody or control Ig during the allergen challenge phase of allergic inflammation. AHR (A) and lung eosinophilia (B) were quantified as described in Materials and methods. IL-5 (C), IL-13 (D), and IL-10 (E) levels were determined in lung homogenate supernatant by ELISA. Data are expressed as means ± SEM (A) or medians (B–E; n = 4–6 mice/group). *, P < 0.05 compared with OVA-sensitized mice that received PBS and control Ig.

Figure 4. Transfer of IL-10-deficient CD4⁺CD25⁺ regulatory T cells suppresses allergen-induced airway inflammation. Mice received either wild-type CD4⁺CD25⁺ regulatory T cells, IL-10-deficient CD4⁺CD25⁺ regulatory T cells, or an equivalent volume of PBS as a control. AHR (A) and lung eosinophilia (B) were determined as described in Materials and methods. IL-5 (C), IL-13 (D), and IL-10 (E) levels were measured in lung homogenate supernatant by ELISA. Data are expressed as means ± SEM (A) or medians (B–E; n = 6–11 mice/group from two separate experiments). *, P < 0.05 compared with OVA-sensitized mice that received PBS instead of CD4⁺CD25⁺ cells.
IL-10 during allergen-induced airway inflammation. Intracellular cytokine analysis of lung tissue digest cells showed that IL-10 is produced primarily from CD4+ T cells (Fig. 5, A and B). We could not find appreciable IL-10 production from other cells such as CD8+ T cells, macrophages, dendritic cells, B cells, or granulocytes during allergic lung inflammation. Moreover, transfer of CD4+CD25+ regulatory T cells increased the percentage of CD4+ cells producing IL-10 compared with PBS alone (Fig. 5, A and B). This increase in CD4+IL-10+ cells was not dependent on the ability of the transferred CD4+CD25+ regulatory T cells to produce IL-10 because a similar increase in CD4+IL-10+ cells was seen after transfer of IL-10-deficient CD4+CD25+ regulatory T cells. Thus, CD4+CD25+ regulatory T cells suppressed allergen-induced airway inflammation by inducing IL-10 production from CD4+ cells in the lungs of OVA-sensitized mice.

**DISCUSSION**

In this paper we show for the first time that allergen-specific CD4+CD25+ T regulatory cells can suppress multiple pathophysiological features of allergic airway disease in vivo. Transfer of these allergen-specific CD4+CD25+ T regulatory cells reduced AHR, Th2 cell and eosinophil recruitment, and Th2 cytokine secretion. Importantly, we show that this effect is dependent on IL-10 because a neutralizing anti–IL-10R antibody abrogated suppression by CD4+CD25+ regulatory T cells. Moreover these effects were found to be independent of production of IL-10 by the CD4+CD25+ regulatory cells themselves.

Previous studies have determined that CD4+CD25+ regulatory T cells are able to regulate autoimmune immunopathologies, which are generally of a Th1 cell type (7, 15, 16), although a recent study using a *Leishmania major* infection model in SCID mice confirmed that both Th1 and Th2 cell function can be suppressed by naturally occurring CD4+CD25+ T regulatory cells (17). Other studies have implied that CD4+CD25+ T cells may be able to suppress some aspects of allergic pathology, but these have all involved complex transgenic models or cell transfer into T cell–deficient recipient mice (10–12). We have shown that transfer of CD4+CD25+ T regulatory cells into a classical model of systemic allergen sensitization in immunocompetent mice reduces multiple pathophysiological parameters, including both allergen-induced airway inflammation and AHR. These findings support our conclusions from human studies in vitro, which argue that an imbalance between suppression and activation exists in patients with allergic disease (9).

Transfer of allergen-specific CD4+CD25+ T cells into OVA-sensitized mice reduced eosinophilia and AHR, together with Th2 cell numbers and Th2 cytokine production. This implies that there is an effect on either Th2 cell trafficking or in local expansion of allergen-specific Th2 cells. However, the lack of effect on Th2-attracting chemokines such as CCL22, CCL17, and CCL11 suggests that Th2 cell recruitment can still occur. Although we saw decreases in Th2 cytokine secretion after transfer of CD4+CD25+ T cells, there was no accompanying reduction in serum IgE production. This might seem surprising because CD4+CD25+ T cells have previously been reported to suppress IgE in a transgenic model of hyper IgE (18). In addition, patients with immunodysregulation, polyendocrinopathy, enteropathy, X-linked syndrome who lack CD4+CD25+ regulatory T cells because of a mutation in Foxp3 exhibit elevated serum IgE levels (19). However, IL-10 has been shown to actually increase IgE production from B cells that have already switched but inhibits germline class switch (20). The lack of change in IgE in our model probably reflects the comparably short time course of the model and the timing of CD4+CD25+ T cell transfer.

The mechanism of suppression by allergen-specific CD4+CD25+ T regulatory cells is controversial. In vitro, the phenomenon is contact dependent but can be observed in the
absence of either IL-10 or TGF-β (9, 21, 22). In contrast, in vivo experiments in a colitis model suggest that IL-10 and TGF-β are involved in the suppression mediated by these cells (15). However, the effect may be model dependent because it was not observed in a gastritis model (23). We show that IL-10 but not TGF-β is up-regulated in the lung after transfer of allergen-specific CD4+CD25+ T regulatory cells and that this is observed together with an abrogation of AHR and allergic inflammation. Moreover, we highlight the importance of this IL-10 by showing that neutralizing anti–IL-10R antibody treatment abolished the suppressive effect of the CD4+CD25+ regulatory T cells so that AHR, eosinophilia, and Th2 cytokine levels were comparable to those seen in the absence of regulatory cells. IL-10 has previously been reported to be a potential regulatory factor in allergen-induced airway inflammation because transfer of engineered IL-10–producing T cells reduced AHR and inflammation in a murine model (24). Although this study showed that neutralization of IL-10 in the lung worsened allergic inflammation, we did not find that anti–IL-10R treatment had any effect on OVA-sensitized mice in the absence of transferred CD4+CD25+ regulatory T cells. This may be because of differences in the time of IL-10 neutralization. Oh et al. administered anti–IL-10 during both sensitization and challenge phases of allergen-induced airway inflammation, whereas we have blocked during the challenge phase only (24).

We have shown that the suppression by CD4+CD25+ regulatory T cells was not dependent on IL-10 production from allergen-specific T regulatory cells themselves, because the suppressive effect was preserved in CD4+CD25+ cells isolated from OVA-transgenic IL-10−/− mice. Interestingly, Asseman et al. previously reported that IL-10−/− CD4+CD25+ T cells could inhibit colitis induced by transfer of naive but not antigen-experienced T cells (25). In our model, suppression was seen after transfer of IL-10−/− CD4+CD25+ T cells into mice that had been sensitized to OVA and, thus, presumably OVA-experienced Th2 cells were present. The differential dependence on IL-10 may reflect differences in the degree of inflammation and T cell activation in the gut in the colitis model compared with our lung model but is in keeping with data from a gastritis model (23).

IL-10 expression in the airway was still elevated after transfer of IL-10−/− CD4+CD25+ T cells, suggesting that the regulatory T cells may induce IL-10 production in another cell population within the lung. These could be CD4+CD25− T cells, which, in humans, have been reported to acquire a regulatory phenotype dependent on IL-10 production after in vitro co-culture with CD4+CD25+ T cells (26). In addition, a recent report also suggests that CD4+CD25+ T cells might not be the only source of IL-10 in a model of infectious tolerance with CD4+CD25+ T cells during experimental allergic encephalomyelitis (27). Here, we show for the first time that the percentage of pulmonary CD4+IL-10–producing cells is increased after transfer of CD4+CD25+ regulatory T cells in vivo. Although we cannot exclude the possibility that other cells contribute to IL-10 production, we did not find expression in macrophages, dendritic cells, or granulocytes. Interestingly, we found IL-10 production by CD4+ cells was similarly increased after transfer of IL-10−/− deficient CD4+CD25+ regulatory T cells. This implies that CD4+CD25+ regulatory T cells suppress inflammation via induction of IL-10 from CD4+ T cells and that production of IL-10 from the regulatory cells themselves is not required. Thus, our data may reconcile the apparent contradiction in previous in vitro and in vivo reports because suppression in vivo may rely on the induction of IL-10 from recipient CD4+ T cells.

The data presented in this paper suggest that induction of IL-10 in vivo by T regulatory cells may represent a novel treatment for allergic asthma. Indeed, it has been previously demonstrated that nonallergic individuals have a higher percentage of allergen-specific IL-10–producing cells, whereas allergic individuals are characterized by a higher percentage of allergen-specific IL-4–producing cells (8). Strategies for inducing IL-10 may include expansion of the naturally occurring CD4+CD25+ population or enhancement of regulatory T cell function by drugs such as corticosteroids, as shown previously in vitro (28). Alternatively it may be possible to induce populations of IL-10–producing or TGF-β surface-positive T regulatory cells in vivo, as has been described in several different murine systems using mycobacterial exposure, airway allergen delivery before sensitization and challenge, or in vitro derivation by stimulation in the presence of immunosuppressive drugs (29, 30, 31, 16). Allergen immunotherapy has been used for many years to control symptoms in a variety of allergic diseases, and current data suggest that this may induce IL-10–producing regulatory T cell populations (32, 33). Peptide therapy induced IL-10–producing regulatory cells in mice (34), and recent data suggest that allergen-derived T cell peptides may also reduce features of asthma in humans through induction of IL-10 (35).

In conclusion, we provide for the first time direct evidence to show that transfer of allergen-specific CD4+ CD25+ T regulatory cells to sensitized mice abrogates the features of allergic airway disease in vivo. These include reduced eosinophil and Th2 cell recruitment, AHR, and Th2 cytokine production. Down-regulation of inflammation was observed with a concomitant increase in pulmonary IL-10 production from CD4+ T cells. Blocking studies showed that the suppressive effect was dependent on IL-10, but, importantly, the effect was not dependent on IL-10 production from the CD4+CD25+ regulatory T cells themselves. Thus, our data suggest that strategies designed to maximize the function of T regulatory cells in vivo could be of benefit to allergic asthmatic patients in the future.

MATERIALS AND METHODS

Mice
Female BALB/c mice were purchased from Harlan. As a source of allergen-specific CD4+CD25+ regulatory T cells, DO11.10 mice expressing the transgene for the DO11.10 α6β TCR, which recognizes residues 323–339
of chicken OVA in association with I-A^d, were used. These mice were originally generated by D. Loh (Washington University, St. Louis, MO) (36) and were provided by J. Skok (Imperial College, London, UK). Animals were housed at the Imperial College London animal facility and were used at 6–8 wk of age. Food and water were supplied ad libitum. UK Home Office guidelines for animal welfare based on the Animals (Scientific Procedures) Act of 1986 were strictly observed. DO11.10 mice crossed to IL-10-deficient mice on a BALB/c background were a gift of K. Rajewsky (University of Cologne, Cologne, Germany) (37).

**Isolation of CD4^+CD25^+ regulatory T cells**

DO11.10 and DO11.10 IL-10-deficient mice were killed by cervical dislocation, and OVA-specific CD4^+CD25^+ cells were isolated from the spleen and peripheral lymph nodes using a CD4^+CD25^+ regulatory T cell isolation kit according to the manufacturer’s protocol (Miltenyi Biotec). Purity was assessed by flow cytometric analysis (as described in Staining of BAL... and was typically >90%.

**In vitro assessment of regulatory capacity**

BALB/c mice were sensitized using OVA (Sigma-Aldrich) at a concentration of 0.1 mg/mouse in 0.2 ml alum (AALGel-S, SERVA Electrophoresis) i.p. 1 wk later, mice were killed by cervical dislocation. Spleens were recovered from mice, and single-cell suspensions were prepared. Splenocytes were cultured in triplicate at 5 × 10^5 splenocytes/well in flat-bottomed 96-well plates in the presence of complete media alone or with 100 μg/ml OVA for 48 h. Complete media consisted of RPMI 1640 (Sigma-Aldrich) containing 10% FCS (Invitrogen), 5mM l-glutamine (Invitrogen), and 10 U/ml penicillin and 100 mg/ml streptomycin (Sigma-Aldrich). The cells were incubated for a further 18 h in the presence of 1 μCi/well [3H]thymidine (MP Biomechanical) to quantify cell proliferation. To assess the suppressive capacity of freshly isolated CD4^+CD25^+ regulatory T cells, these cells were isolated from DO11.10 spleen and peripheral lymph nodes and added at 1.25 × 10^5 cells/well. To assess the proliferative capacity of isolated CD4^+CD25^- cells alone, splenocytes were irradiated at 3,000 rad and cultured with CD4^+CD25^- cells. [3H]thymidine incorporation data in cpm was converted to stimulation index (fold increase = cpm with OVA / cpm of medium only condition).

**Induction of AHR and eosinophilia**

BALB/c mice were sensitized using OVA (Sigma-Aldrich) at a concentration of 0.1 mg/mouse in 0.2 ml alum on day 0. Control mice received the same volume of PBS. On day 6, mice received either 5 × 10^4 CD4^+CD25^- cells intravenously in PBS or the same volume of PBS as a control. In some experiments, OVA-specific CD4^+CD25^- T cells were injected as a further control. All groups of mice were challenged daily with 5% OVA (aeroallergen) for 6 h before intravenous injection of mice (aeroallergen) for 20 min via the airways between days 7 and 12. In some experiments, mice were dosed with 250 μg anti–IL-10R (1B1.3) 30 min before the first, third, and fifth OVA challenge. Mice were killed by exanguination under terminal anesthesia at 24 h after the final OVA challenge.

**Measurement of AHR**

Airway responsiveness was measured in mice 24 h after the final OVA challenge by recording respiratory pressure curves by whole-body plethysmography (Buxco Electronics) in response to inhaled methacholine (Sigma-Aldrich) at concentrations of 3–30 mg/ml for 1 min, as described previously (38). Results are shown for Penh after allergen challenge. Penh results were confirmed by direct measurements of RL and Cdyn in anaesthetized and tracheostomized mice in response to inhaled methacholine at concentrations of 3–100 mg/ml in a Buxco system (Buxco Electronics) in a modified version of previously described methods (39).

**Cell recovery**

**Airway lumen.** BAL was performed as previously described (3). In brief, the airways of the mice were lavaged three times with 0.4 ml PBS via a tracheal cannula. BAL fluid was centrifuged at 200 g for 5 min at 4°C. Cells were counted and pelleted onto glass slides by cytocentrifugation (5 × 10^4 cells/slide). Differential cell counts were performed on Wright-Giemsa-stained (Thermo) cytocentrifuge slides. Percentages of eosinophils, lymphocyte/mononuclear cells, neutrophils, and macrophages were determined by counting their number in eight randomly selected high power fields (40×; total area = 0.5 mm^2/area) and dividing this number by the total number of cells counted. To obtain absolute numbers of each leukocyte subtype, these percentages were multiplied by the total number of cells obtained in the lavage fluid. All differential counts were performed blind and in a randomized order at the end of the study by the same observer (J. Kealey).

**Lung parenchyma.** To disaggregate the cells from the lung tissue, one lobe (~100 mg) of lung was incubated at 37°C for 1 h in digest reagent (0.15 mg/ml collagenase [type D; Roche], 25 μg/ml DNase [type 1; Roche]) in complete media. The recovered cells were filtered through a 70-μm nylon sieve ( Falcon), washed twice, resuspended in complete media, and counted in a hemocytometer (VWR). Cytocentrifuge preparations were prepared and Wright-Giemsa stained, and differential counts were performed as for BAL.

**Draining lymph nodes.** Draining lymph nodes were removed, weighed, and filtered through a 70-μm nylon sieve. The resulting single cell suspension was centrifuged at 200 g for 5 min at 4°C, resuspended in complete media, and counted in a hemocytometer.

**Lung tissue histopathology**

Lungs were fixed in 10% normal buffered formalin. 4-μm paraffin-embedded sections were stained with hematoxylin and eosin.

**Staining of BAL, lung, and lymph node cells for flow cytometric analysis**

Suspensions of BAL and lung tissue and lymph node cells were stained in PBS containing 1% FCS and 0.01% sodium azide. To reduce nonspecific binding, cells were incubated with rabbit serum ( Sigma-Aldrich) for 15 min before staining. The antibodies used were anti-mouse CD4, anti–mouse CD11b, anti–mouse CD11c, anti–mouse B220, anti–mouse CD8, anti–mouse IL-10 and its iso type control (all obtained from BD Biosciences), anti–mouse T1/ ST2 (Morwell Diagnostics), and anti–mouse KJ1–26 and its iso type control (Caltag). Cells were stained for 20 min on ice, washed twice, and fixed in cellfix (Becton Dickinson). For intracellular cytokine staining, cells were stimulated with PMA/ ionomycin (Merek) in the presence of Brefeldin A (Sigma-Aldrich) for 6 h before extracellular staining. After staining and fixing, cells were permeabilized using 0.5% saponin (Sigma-Aldrich) and stained with anti–IL-10 antibody or the appropriate iso type control. Flow cytometric analysis was performed using a FACSCalibur (Becton Dickinson).

**Cytokine analysis**

Cytokines were analyzed in BAL samples and lung-tissue homogenate supernatants. Lung tissue was homogenized at 50 mg/ml in HBSS (Invitrogen) and centrifuged at 800 g for 10 min and the supernatant was collected. Paired antibodies for murine IFN-γ and TGFB-B (BD Biosciences), IL-5 (Endogen), eotaxin/CCL11, and TARC/CCL17 (R&D Systems) were used in standardized sandwich ELISAs according to the manufacturer’s protocol. MDC/CCL22 levels were measured using a sandwich ELISA generated by coating ELISA plates with anti–mouse MDC (a gift from ICOS Corp., Bothell, WA) and detecting bound antibody with biotinylated anti–mouse MDC (R&D Systems) against a standard curve generated using recombinant MDC (R&D Systems) as previously described (40). ELISA kits to measure IL-13 and IL-10 were purchased from R&D Systems and ebioscience, respectively, and were used according to the manufacturer’s protocol.

**IgE**

Levels of total IgE were measured in serum by ELISA using paired antibodies according to the manufacturer’s instructions (BD Biosciences). Levels of...
anti-OVA IgE were measured in serum and lung homogenate supernatant by ELISA as described previously (41).

Data analysis
Data are expressed as medians unless otherwise stated. Statistical significance between groups was tested using a Mann-Whitney U Test. A p-value of <0.05 was considered significant. Graph generation and statistical analysis were performed by using Prism software (version 4.00; GraphPad).

Online supplemental material
Fig. S1 shows that allergen-specific CD4+CD25+ regulatory T cells suppress allergen-induced proliferation in vitro. Fig. S2 shows that allergen-specific CD4+CD25+ regulatory T cells are able to migrate to the airway lumen, lung tissue, and draining lymph nodes in vivo. Fig. S3 shows that transfer of CD4+CD25+ regulatory T cells suppresses changes in RL and Cdyn. Fig. S4 shows that proinflammatory chemokine levels in the lung are unaffected by transfer of CD4+CD25+ regulatory T cells. Fig. S5 shows that transfer of CD4+CD25+ regulatory T cells has no effect on serum IgE levels.

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REFERENCES


