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

Jennifer Kearley, Jane E. Barker, Douglas S. Robinson, and Clare M. Lloyd

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.

Asthma, which affects ~5% of the population of the Western world, is characterized by bronchial eosinophilic inflammation and airway hyperreactivity (AHR). Although it is predominantly eosinophils that are recruited to the lung, recent evidence suggests that T cells play an important effector role in this process both in human asthma and murine models because lung eosinophilia and AHR are abrogated in T cell–deficient mice (1, 2, 3). T helper type 2 (Th2) cells release IL-4, IL-5, and IL-13 and have been shown to mediate allergic reactions (4). The regulation of T cell responses is an important process in vivo in order to provide immunity to invading pathogens while preventing excessive inflammatory responses to self-antigens. There is now increasing evidence of the existence of regulatory T cell subsets capable of suppressing immune responses (5). One of the best characterized of these is the “naturally occurring” CD4⁺CD25⁺ regulatory T cells. The precise mechanisms by which CD4⁺CD25⁺ regulatory cells suppress inflammation are unknown, though there is evidence for the involvement of IL-10 and TGF-β in some settings, as administration of antibodies against these cytokines prevent the abrogation of colitis by CD4⁺CD25⁺ regulatory T cells in a mouse model and also block the suppressor activity of T regulatory cells isolated from human peripheral blood (6, 7, 8).

Although the ability of CD4⁺CD25⁺ regulatory T cells to suppress Th1 cell–mediated diseases has been extensively studied, their role in controlling Th2 cell–mediated allergic responses is the subject of more recent investigation and have thus far been limited to in vitro and complex in vivo studies. It has been shown that CD4⁺CD25⁺ regulatory T cells isolated from hay fever patients have an impaired ability...
to suppress proliferation and IL-5 production of CD4+CD25− T cells compared with healthy controls (9). Mouse studies have shown that Th2 cell–polarized CD4+ T cells depleted of the CD4+CD25+ population resulted in increased airway eosinophilia compared with unfraccionated T cells after adoptive transfer of the Th2 cells (10). Moreover, double transgenic mice with T cells that express the T cell receptor for OVA (DO11.10), as well as OVA targeted to the lung epithelium, demonstrated pulmonary infiltrates containing CD4+CD25+ T cells (11). These cells were able to prevent OVA-induced proliferation of CD4+CD25− cells in vitro. In addition, the mice were shown to be tolerant to OVA when spleen cells were removed and challenged ex vivo. However, if exogenous OVA was given to the mice, AHR still developed, although lung eosinophilia and ex vivo Th2 responses were reduced. In a different model, cotransfer of CD4+CD25+ T cells with CD4+CD25− T cells from mice sensitized to OVA into T cell–deficient Rag−/− hosts inhibited both allergen-induced airway inflammation and IL-4 expression (12). Although these studies imply that CD4+CD25+ regulatory T cells may have a beneficial role in suppressing allergen-induced airway inflammation in vivo, this has not yet been clearly demonstrated.

In the present study, we have determined the effect of allergen-specific CD4+CD25+ regulatory T cells on the development of allergen-induced pulmonary inflammation using a well-characterized in vivo murine model involving systemic sensitization and airway challenge with antigen. We have demonstrated that transfer of allergen-specific CD4+CD25+ regulatory T cells from DO11.10 transgenic mice inhibited the classical pathology associated with allergic asthma, namely AHR, lung eosinophilia, and Th2 cytokine production. Blocking experiments determined that this effect is dependent on IL-10. Moreover, we have shown that CD4+CD25+ regulatory T cells exerted their suppressive effects in vivo independently of their capacity to produce IL-10 but induced IL-10 production from recipient CD4+ T cells.

RESULTS

Allergen-specific CD4+CD25+ regulatory T cells suppress T cell proliferation in vitro and migrate to the lung in vivo

Antigen-specific CD4+CD25+ T cells were isolated from spleen and lymph nodes of DO11.10 αβ TCR transgenic mice. We confirmed regulatory activity of the isolated cells using in vitro cultures stimulated with OVA and APCs. The OVA-specific CD4+CD25+ T cells did not themselves proliferate on stimulation with antigen, but suppressed proliferation of splenocytes from OVA-sensitized BALB/c mice (Fig. S1, available at http://www.jem.org/cgi/content/full/jem.20051166/DC1).

Allergen-specific CD4+CD25+ regulatory T cells were transferred into BALB/c mice 24 h before airway allergen challenge. Flow cytometric analysis of bronchoalveolar lavage (BAL), lung tissue and draining lymph nodes confirmed that transferred DO11.10 CD4+CD25+ cells were present in the airway lumen, lung, and lymph nodes of OVA-sensitized mice after allergen challenge (Fig. S2, available at http://www.jem.org/cgi/content/full/jem.20051166/DC1). Transferred cells were not detected in the sham-sensitized mice that received alum/PBS.

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).
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+ 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 costaining cells with CD4 and the Th2 cell–specific marker T1/ST2 (13). 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).
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 regulatory T cells (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 IL-10.
IL-10 during allergen-induced airway inflammation. Intra-
cellular 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, den-
dritic 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.

<table>
<thead>
<tr>
<th>Population</th>
<th>% of population producing IL-10 in the lung (Median (range))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD4⁺ T cells</td>
<td>0.9 (0.3-1.6)</td>
</tr>
<tr>
<td>CD8⁺ T cells</td>
<td>0.0</td>
</tr>
<tr>
<td>Macrophages</td>
<td>0.0</td>
</tr>
<tr>
<td>Dendritic cells</td>
<td>0.0</td>
</tr>
<tr>
<td>B cells</td>
<td>0.3 (0.1-0.4)</td>
</tr>
<tr>
<td>Granulocytes</td>
<td>0.0</td>
</tr>
</tbody>
</table>

![Figure 5](image_url)

**Figure 5.** IL-10 is produced by CD4⁺ T cells during allergen-induced
airway inflammation and is increased by transfer of CD4⁺CD25⁺
regulatory T cells. Lungs were digested with collagenase and DNase
as described in Materials and methods. Digest cells were stimulated by
PMA/Ionomycin in the presence of Brefeldin A for 6 h. Cells were phenotyped
by staining for CD4, CD8, CD11b (macrophages), CD11c (dendritic cells), and
B220 (B cells). Granulocytes were defined by forward and side scatter. (A) Data
are expressed as median cell types producing IL-10 with interquartile
range (n = 6–14 mice/group in three separate experiments), *, P < 0.05
compared to OVA-sensitized mice that received PBS instead of CD4⁺CD25⁺
cells. (B) Data are shown as representative FACs plots showing costaining of
lung tissue digest cells with CD4 and IL-10. Percentages in the top right
quadrants refer to median percentages of CD4 cells expressing IL-10
(n = 6-14 mice/group).

**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 immuno-
pathologies, which are generally of a Th1 cell type (7, 15,
16), although a recent study using a *Leishmania major*
infestation 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 as-
pects of allergic pathology, but these have all involved com-
plex 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 sys-
temic allergen sensitization in immunocompetent mice re-
duces multiple pathophysiological parameters, including both
allergen-induced airway inflammation and AHR. These find-
ings support our conclusions from human studies in vitro,
which argue that an imbalance between suppression and activa-
tion exists in patients with allergic disease (9).

Transfer of allergen-specific CD4⁺CD25⁺ T cells into
OVA-sensitized mice reduced eosinophilia and AHR, to-
gether with Th2 cell numbers and Th2 cytokine produc-
tion. 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, pa-
tients with immunodysregulation, polyendocrinopathy, en-
teropathy, X-linked syndrome who lack CD4⁺CD25⁺ reg-
ulatory 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 results 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 αβ TCR, which recognizes residues 323–339
of chicken OVA in association with I-Aκ, 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 (Au-Gel-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 5×10^6 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 100 U/ml penicillin and 100 μg/ml streptomycin (Sigma-Aldrich). The cells were incubated for a further 18 h in the presence of 1 μCi/well [methyl-3H]thymidine (MP Biochemicals) 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 in alum. On day 6, mice received either 5×10^5 cells of OVA (Sigma-Aldrich) at a concentration of 0.1 mg/mouse in 0.2 ml alum (Au-Gel-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 5×10^6 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 100 U/ml penicillin and 100 μg/ml streptomycin (Sigma-Aldrich). The cells were incubated for a further 18 h in the presence of 1 μCi/well [methyl-3H]thymidine (MP Biochemicals) 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).

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 μg/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 Cdvn 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 (5×10⁴ cells/slide). Differential cell counts were performed on Wright-Giemsa-stained (Thermo) cytopsins. 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 mm²/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. Kearley).

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 isotype control (all obtained from BD Biosciences), anti–mouse T1/T2 (Morwell Diagnostics), and anti–mouse KJ1-26 and its isotype 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 (Merck) 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 isotype 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 wascollected. Paired antibodies for murine IFN-γ and TGF-β (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 ICS Corp., Bothell, WA) and detecting bound antibody with biotynylated 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.

We would like to thank Catherine Hawrylowicz and Darren Campbell for critical readings of this manuscript. We would also like to thank Lorraine Lawrence for histological sectioning and staining and Rute Marques for help in preparing the D011.10/lL-10-deficient splenocyte suspensions.

This work was supported by the Wellcome Trust (057704) and AstraZeneca. J. Kearley is supported by a Biotechnology and Biological Sciences Research Council/ Cooperative Award in Science and Engineering studentship, D.S. Robinson is supported by a Wellcome Trust Research Leave Award for Clinical Academics, and C.M. Lloyd is supported by a Wellcome Senior Fellowship in Basic Biomedical Sciences. The authors have no conflicting financial interests.

Submitted: 9 June 2005
Accepted: 18 October 2005

REFERENCES


