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J Immunol published online 26 August 2011
http://www.jimmunol.org/content/early/2011/08/26/jimmunol.1100436

Supplementary Material http://www.jimmunol.org/content/suppl/2011/08/26/jimmunol.1100436.DC1

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IFN-γ Acts on the Airway Epithelium To Inhibit Local and Systemic Pathology in Allergic Airway Disease

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Inhibiting allergic airway inflammation is the goal of therapy in persistent asthma. Administration of medication via the airways delivers drug directly to the site of inflammation and avoids systemic side effects but often fails to modulate systemic features of asthma. We have shown that Th1 cells, through production of IFN-γ, inhibit many Th2-induced effector functions that promote disease. Using a newly generated mouse that expresses IFN-γR only on airway epithelial cells, we show that the airway epithelium controls a range of pathological responses in asthma. IFN-γ acting only through the airway epithelium inhibits mucus, chitinases, and eosinophils, independent of Th2 cell activation. IFN-γ signaling through the airway epithelium inhibits eosinophil generation in the bone marrow, indicating that signals on the airway mucosal surface can regulate distant functions to inhibit disease. IFN-γ actions through the airway epithelium will limit airway obstruction and inflammation and may be therapeutic in refractory asthma. The Journal of Immunology, 2011, 187: 000–000.

In asthma, CD4 Th2 cells are present in the airways during acute exacerbations of disease and remain active even when symptoms are quiescent (1, 2). Animal studies show that CD4 Th2 cells are required for development of Ag-induced allergic airway inflammation, and overexpression of the Th2 cytokines, IL-4, IL-5, and IL-13, results in features associated with chronic asthma (3–5). Th2 cytokines promote airway eosinophilia and increased production of mucus and chitinases leading to disease. Airway epithelial cell mucus hypersecretion is IL-13 dependent and contributes significantly to airway obstruction and death during acute exacerbations of asthma (6, 7). Airway eosinophilia correlates both with disease activity and severity (8). IL-5 and IL-13 stimulate bone marrow (BM) production of eosinophils and recruitment of eosinophils to the respiratory tract (9). Chitinases, produced by airway epithelial cells and macrophages, are induced by IL-4 and IL-13 in the airways of asthmatics, are associated with disease severity, and promote inflammation (10). These important Th2-dependent effects indicate asthma’s scope, with both local and systemic contributions to disease development and activity. Inhibition of Th2 cell function and/or blockade of Th2 effector responses are the goals of therapy in asthma. Still, in many cases, standard therapies do not effectively inhibit disease, or their long-term use is limited because of adverse systemic effects.

Materials and Methods

Mice

OT-II mice, which are transgenic for the TCR recognizing OVA peptide 323–339, were bred in our facilities and backcrossed to B6.PL-Thy1.2 mice (The Jackson Laboratory, Bar Harbor, ME). OT-II Thy1.1 and OT-II Thy1.1/2 mice were used for the generation of Th1 and Th2 cells. C57BL/6 mice and Ifngr1−/− mice (The Jackson Laboratory or National Cancer Institute, Frederick, MD) were used as recipients of cell transfers at 6–8 wk of age. IL-5 transgenic mice were used as donors for eosinophil migration assays (23). All experimental protocols were approved by the Yale Animal Care and Use Committee.

Generation and confirmation of epi-IFN-γR mice

To generate “epi-IFN-γR” mice, a construct was generated containing the murine IFN-γR1 cDNA (provided by Dr. R. Schreiber, Washington University, St. Louis, MO) with a 39-bp human c-myc tag inserted after the

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Histological mucus index

Formalin-fixed, paraffin-embedded lungs were stained with PAS. A histological mucus index (HMI) was calculated using periodic acid-Schiff (PAS)-stained lung sections as described previously (13). This index is the equivalent to the linear percent of epithelium positive for mucus and was calculated for each mouse lung by a blinded investigator, and then, the mean of the HMI was calculated for each experimental group.

Data analysis

Data are reported as mean ± SE. Statistical significance was determined by unpaired Student t test using the Bonferroni correction for multiple comparisons.

Results

IFN-γ inhibits Th2-induced mucus, chitinas, and eosinophil

Our previous studies established that Th1 cells, through production of IFN-γ, inhibit Th2-induced effector functions (14). Those studies, in BALB/c mice, revealed that IFN-γ inhibited Th2 effects in the lung. In the current studies, using C57BL/6 mice, we investigate the specific mechanisms by which Th1 cells and IFN-γ inhibit critical pathogenic features of allergic airway inflammation, focusing on mucus hyperproduction, increased chitinase activity, and airway eosinophilia. To study how Th1 cells inhibit Th2 cell effects, we cotransferred OVA-specific OT-II Th1 and Th2 cells into C57BL/6 recipient mice. After adoptive transfer, mice were exposed to inhaled OVA over 9 d, and both Th1 and Th2 cells were recruited to the lung. Th1 cells inhibited Th2 cell-induced mucus staining, chitinase activity, and eosinophilia in the airways (Fig. 1A) and lung (data not shown). Th1 and Th2 cells were distinguished by congenic markers for Thy1 
 or Thy1 
. Th2 cytokines and the number of Th2 cells were comparable in mice that received either transfer of Th1+Th2 cells or Th2 cells alone (Supplemental Fig. 1). Therefore, Th1 cells inhibit these Th2 cell effects in the presence of activated Th2 cells in the respiratory tract. Although it is well known that IFN-γ can modulate Th2 cell cytokine production (18), in this study, Th1 inhibition is present even with active Th2 cell function.

In mice that received cotransfer of Th1+Th2 cells, inhibition of mucus staining was associated with markedly reduced expression of muc5AC, the predominant airway mucin gene induced in allergic inflammation (Fig. 1B, 1C). Reduced chitinase activity was associated with a striking reduction in gene expression of AMCase, the most abundant chitinase released in the murine respiratory tract (Fig. 1B). When IFN-γ effects were eliminated in recipient mice deficient of IFN-γR, mucus and chitinase activity were no longer inhibited (Fig. 1A). Th1 cells, through production of IFN-γ, profoundly inhibit the production of mucus and chitinas.

Eosinophils in the airway and lung (data not shown) were both low in C57BL/6 mice after cotransfer of Th1+Th2 cells compared with mice that received Th2 cell transfer alone (Fig. 1A). Eosinophilia was partially restored in ifngr1 
 mice, indicating that IFN-γ and other factors produced by Th1 cells inhibit eosinophils in C57BL/6 mice. Tissue eosinophilia is a complex process that requires eosinophil expansion in the BM, release and recruitment, and in the lung, these effects are mediated in large part by Th2 cytokines and eotaxin-1 (CCL11) (9). Th2 cell transfer and inhaled OVA stimulated increased BM eosinophilopoiesis, and this was blocked in mice that received Th1+Th2 cells (Fig. 1B). Eosinophil chemotactic activity in the BALF was increased in mice that received Th2 cells alone and was inhibited after transfer of Th1+Th2 cells (Fig. 1B). Inhibition of chemotaxis in mice that received Th1+Th2 cells was not explained by reduced eotaxin-1, because eotaxin-1 levels were higher in mice that received Th1+Th2 cells compared with Th2 cells alone (Th2, 2 ± 0.2)
pg/ml versus Th1+Th2, 1335 ± 337 pg/ml; p = 0.06). The IFN-γ–inducible chemokine inflammatory protein-10 (CXCL10) was increased in the BAL of mice that received Th1+Th2 cells compared with Th2 cells alone (Th2, 202 ± 10 pg/ml versus Th1+Th2, 9791 ± 1378 pg/ml; p = 0.02), and past studies suggest that through binding to CXCR3, CXCL9 and CXCL10 can control eosinophil recruitment (27). When Th1+Th2 cells were transferred cells into mice deficient in CXCR3, followed by inhaled OVA exposure, eosinophils were equivalently reduced in cxcr3+/+ and cxcr3−/− animals (Supplemental Fig. 2). Therefore, reduced chemoattraction of eosinophils after cotransfer of Th1+Th2 cells is not due to a reduction in CCL11 or inhibitory effects of CXCR3-dependent chemokines. In summary, Th1 cells, by production of IFN-γ, reduce Th2-induced mucus and chitinase production and inhibit airway eosinophilia by reducing eosinophil generation and chemotaxis. These data show that IFN-γ inhibits three critical pathologic Th2 effects in the respiratory tract by acting at both local and distant sites.

**Generation of mice with IFN-γR expressed only on airway epithelial cells**

Given the contribution of the airway epithelium to mucus and chitinase production and its importance in immune modulation in the lung, we hypothesized that IFN-γ, acting though airway epithelial cells, could provide potent inhibition of Th2-induced effects in the respiratory tract. We generated epi-IFN-γR mice that express IFN-γRs only on airway epithelial cells. Transgenic mice were generated by construction of a plasmid containing murine ifngr1 cDNA under control of a constitutively activated rat CC10 promoter (24). Transgene-positive mice were backcrossed to ifngr1−/− mice to generate epi-IFN-γR mice. IFN-γR expression was high in the lungs from ifngr1+/− and epi-IFN-γR mice and very low in the spleens of both epi-IFN-γR and ifngr1−/− mice (Fig. 2A), indicating lung-specific expression of IFN-γR in epi-IFN-γR mice.

**FIGURE 1.** Th1 cells and IFN-γ inhibit Th2-induced airway pathology. WT (C57BL/6) or ifngr1−/− mice received Th1, Th2, or Th1+Th2 cells and inhaled OVA. A, HMI calculating airway mucus staining in lung sections, chitinase activity in BALF and BAL eosinophils (n = 5 mice/group). B, qPCR analysis of muc5AC and AMCase expression in whole lung (n = 2/group). Eosinophils in the BM and eosinophil migration in response to BALF (n = 2–4/group). C, Mucus staining of lung sections stained with PAS (scale bar, 100 μm) (n = 5/group). Mean levels (±SEM) are shown. These data are each representative of three independent experiments. Chitinase activity in naive mice: WT, 165 U; ifngr1−/−, 220 U. *p, 0.015, Th1+Th2 compared with Th2; #p, 0.0003, Th1+Th2 compared with Th1; %p, 0.039, Th1+Th2 compared with Th2.

**FIGURE 2.** Airway epithelial-specific expression of IFN-γR in epi-IFN-γR mice. A, qPCR for ifngr1 expression in whole-lung RNA from naive ifngr1−/−, ifngr1+/−, and epi-IFN-γR mice. B, MHC class I expression on epithelial cells (gated on CD45− and cytokeratin+ cells) from lungs of ifngr1−/−, ifngr1+/−, and epi-IFN-γR mice after 3 d of treatment with inhaled IFN-γ or PBS. Black line, IFN-γ treated; gray shaded, PBS treated. Data are representative of three independent experiments (n = 2–3/group). #p, 0.015, epi-IFN-γR compared with ifngr1+/− mice.
FIGURE 3. Th1 cells inhibit Th2-induced airway pathology. WT (C57BL/6), Ifngr1−/−, or epi-IFN-γR mice received Th1+Th2 cells and inhaled OVA. A, HMI (two experiments are shown) and chitinase activity in BALF and BAL eosinophils were assessed (n = 5 mice/group). B, Th2 cell number and IL-13 were measured in BAL. C, Eosinophil migration and BM eosinophils. These data are representative of three independent experiments. Mean levels (±SEM) are shown. Chitinase activity in naive mice: WT, 165 U; Ifngr1−/−, 220 U; epi-IFN-γR, 150 U; *p < 0.015, epi-IFN-γR compared with Ifngr1−/− mice; #p < 0.015, epi-IFN-γR compared with Ifngr1−/− mice; n = 6 mice/group). Data are representative of three experiments. #p = 0.02, epi-IFN-γR compared with Ifngr1−/− mice.

To show that epi-IFN-γR mice expressed functional IFN-γR in the lung, mice were treated with inhaled IFN-γ for 3 d, followed by isolation of lung cells and analysis of surface expression of MHC Ags. MHC class I (Fig. 2B) and class II (data not shown) expression were upregulated on the cell surface of epithelial cells isolated from the lungs of Ifngr1−/− mice, whereas in Ifngr1−/− mice, MHC expression was low. In epi-IFN-γR mice, a subpopulation of epithelial cells exhibited upregulation of MHC class I. This subpopulation was consistently 20–22% of lung epithelial cells over multiple experiments. CC10 expression was observed in a comparable percentage of epithelial cells. These data show that epi-IFN-γR mice exhibited restricted IFN-γR expression in the lung and restored IFN-γ-induced functions in airway epithelial cells.

Inhibition of asthma-like features in epi-IFN-γR mice

To determine whether IFN-γ produced by Th1 cells regulates Th2-induced effects via the airway epithelium, we transferred Th1+Th2 cells into epi-IFN-γR mice, followed by exposure to inhaled OVA. In epi-IFN-γR mice, there was near total inhibition of mucus (Fig. 3A, experiment number 1), similar to our observations in Ifngr1−/− mice. In an experiment in which Th2 induction of mucus was more modest, Th1 cells totally inhibited mucus (Fig. 3A, experiment number 2). Thus, in mice with expression of IFN-γR only on airway epithelial cells, there is complete restoration of the inhibitory actions of IFN-γ on mucus. We have previously shown that mucus induction in this model is IL-13 dependent (28); therefore, to ensure that lung Th2 cell infiltration and activation were not different in these strains of mice, we measured Th2 cytokines and Th2 cell numbers in the airways. Comparable levels of IL-13 and Th2 cells were present in BAL from wild-type (WT), Ifngr1−/−, and epi-IFN-γR mice (Fig. 3B), indicating that differential activation and/or recruitment of Th2 cells was not the cause of Th1 inhibition of mucus in epi-IFN-γR mice.

In epi-IFN-γR mice that received Th1+Th2 cells and inhaled OVA, chitinase activity was significantly lower than in mice totally lacking IFN-γR, but complete inhibition was not achieved in any experiment (Fig. 3A).

In epi-IFN-γR mice that received Th1+Th2 cells, BAL eosinophils were reduced almost to the level observed in Ifngr1−/− mice, and this was strikingly lower than observations in Ifngr1−/− mice (Fig. 3B). IFN-γ, signaling only through airway epithelial cells, modulates eosinophilia. These studies show that IFN-γ, through its actions on the airway epithelium, has potent effects. IFN-γ acting through airway epithelial cells totally inhibits airway epithelial mucus production and has partial, but dramatic, inhibitory effects on airway chitinase activity and eosinophils.

IFN-γ acting on the airway epithelium inhibits eosinophilopoiesis

We next asked whether IFN-γ-mediated signals from the airway epithelium inhibit eosinophil development and/or recruitment to the respiratory tract. When mice received Th1+Th2 cells and inhaled OVA, comparable numbers of eosinophils were recovered from the BM of epi-IFN-γR and WT mice, and this was lower than BM eosinophils recovered from Ifngr1−/− mice (Fig. 3C). In contrast, equivalent eosinophil migration was observed in response to BALF from epi-IFN-γR and Ifngr1−/− mice that received Th1+Th2 cell transfer. This suggests that inhibition of airway eosinophils in epi-IFN-γR mice is not due to an IFN-γ-induced effect on chemotactic factors but is due to an epithelial-driven effect on the BM that inhibits eosinophilopoiesis. Levels of the Th2 cytokine, IL-5, were comparable in the BAL in the three

FIGURE 4. Eotaxin-1 does not correlate with lung and BM eosinophils. Eotaxin-1 in BAL from WT (C57BL/6), Ifngr1−/−, or epi-IFN-γR mice that received Th1+Th2 cells and inhaled OVA. Mean (±SEM) is shown (n = 2–8/group). Data are representative of three experiments. #p < 0.00002, epi-IFN-γR or Ifngr1−/− compared with WT mice.
groups of mice (data not shown), as was IL-13 (Fig. 3B), again, indicating equivalent pulmonary Th2 cell activation. We also measured eotaxin-1, because, in addition to its chemokine function, it enhances BM eosinophil differentiation (29), and Th2-induced airway epithelial cell production of CCL11 is inhibited by IFN-γ (30). Eotaxin-1 was equally low in the BAL from ifngr1−/− and epi-IFN-γR mice that received Th1+Th2 cells and very high in WT mice (Fig. 4), indicating eotaxin-1 was unlikely to be controlling eosinophil production in these studies. Because only airway epithelial cells can respond to IFN-γ in epi-IFN-γR mice, IFN-γ appears to stimulate secretion of a factor that controls eosinophil development in the BM.

**Discussion**

These studies show that the airway epithelium has an extensive range of effects in regulating pulmonary allergic inflammatory responses. IFN-γ acting on the airway epithelium inhibits Th2 cytokine effects in epithelial cells and reduces production of eosinophils. Thus, the airway epithelium, responding to IFN-γ from Th1 cells, blocks Th2-induced mucus and chitinase activity locally in the epithelium and remotely in the BM to modulate allergic inflammation. These studies suggest that it may be possible to block some of the pathologic features of asthma using inhaled IFN-γ.

Mucus hypersecretion is a major cause of airway obstruction in asthma leading to cough and wheezing and, in exacerbations, is likely a major cause of death (6). Mucus is produced in mucous glands and by goblet cells in the airways. Goblet cell differentiation from Clara or ciliated airway epithelial cells and require epidermal growth factor receptor activation, IL-13, and phosphorylation of Stat6 (7, 31, 32). IFN-γ may inhibit mucus production through various effects. Past studies have shown that IFN-γ reduces Stat6 phosphorylation in airway epithelial cells (30). Although there is no consensus sequence for Stat6 in the Muc5AC promoter (33), reducing Stat6 phosphorylation may modulate downstream transcription factors, such as SAM pointed domain-containing Ets transcription factor and/or FoxA2, which are essential for goblet cell induction (7, 34, 35). IFN-γ also promotes mucus cell apoptosis (36). Therefore, IFN-γ, by direct actions on the epithelium, may limit goblet cell development, block mucus gene expression, and/or stimulate loss of mucous cells. Importantly, reduced mucus by any means will have a dramatic impact on airway obstruction.

Chitinases are proinflammatory mediators in the lung. Chitinase activity is driven by Th2 cytokines, specifically IL-13 (10). We have shown that IFN-γ inhibits Th2-induced chitinase activity and AMCase transcription. To our knowledge, these are the first studies to show that chitinases are regulated by IFN-γ. Because Th2 cell activation in the lung stimulates chitinase production in airway epithelial cells and macrophages, partial inhibition of chitinase activity may reflect IFN-γ-mediated inhibition in airway epithelial cells but not in macrophages (37). Th2-induced chitinase activity is IL-13 and IL-4Rα1 dependent; therefore, it is possible that IFN-γ inhibits chitinases through negative effects on Stat6 phosphorylation in a manner similar to the effects on mucus described above. Past studies showed a partial reduction in chitinase activity dramatically reduced inflammation (10). The capacity of IFN-γ to reduce chitinases adds to the anti-inflammatory functions of IFN-γ in asthma.

Eosinophil recruitment to the respiratory tract in asthma is a complex process coordinated by cytokines that stimulate eosinophil development, release, and recruitment to the respiratory tract (9). The airway epithelium controls cellular inflammation in the respiratory tract principally by release of factors that regulate cell recruitment, such as chemokines. For example, in mice with CC10-driven deletion of the transcription factor FoxA2, there was increased airway eosinophilia associated with expression of eotaxins (38). Mice with conditional deletion of Stat3 had reduced eosinophilia associated with a reduction in Th2 accumulation and the Th2 chemokine TARC (39). The ability of the airway epithelium to modulate systemic processes in the BM in allergic disease may have been theorized, because the airway produces eotaxin-1 and minute amounts of IL-5 (29, 40), but to our knowledge, this has not been shown in vivo.

Many studies have shown that IFN-γ can inhibit eosinophilia induced in allergic disease. These studies support the ability of IFN-γ to block Th2 cell cytokine production (18) and CD4 T cell recruitment to the lung (19). Although epi-IFN-γR mice exhibited fewer lung and airway eosinophils than ifngr1−/− mice after Th1+Th2 cell transfer, Th2 cells and Th2 cytokines were equivalent. Chemokines produced by airway epithelial cells, such as eotaxins, influence eosinophil recruitment to the lung, thus making them a prime target of IFN-γ effects. Although IFN-γ inhibited human eotaxin-3 (30), its effects on eotaxin-1 were variable in vitro, some studies showing IFN-γ synergizes with other cytokines to increase its expression (41–44). In this study, in ifngr1−/− mice, Th2-induced eotaxin-1 was markedly increased by Th1 cells through IFN-γ and was associated with low eosinophils. This indicates that IFN-γ inhibited eosinophil independent of eotaxin-1. Furthermore, eosinophil chemotaxis in response to BALF from ifngr1−/− and epi-IFN-γR mice was comparable, suggesting that the reduction in eosinophil in epi-IFN-γR mice was not due to differential eosinophil recruitment. BM eosinophils were fewer in epi-IFN-γR mice, indicating reduced development or increased release of eosinophils. Because blood eosinophils were not different among the mice that received Th1+Th2 cells (data not shown), this indicates that IFN-γR activation in the airway epithelium resulted in reduced BM eosinophil production. Eosinophil induction in the BM in allergic disease is dependent on IL-5, which was comparable in BAL in these mice. Eotaxin-1 has also been shown to regulate BM eosinophil development (29), yet there was a lack of association of eotaxin-1 and BM eosinophils. Other possible IFN-γ-driven epithelial effects on eosinophil development include reduced production of other proeosinophil cytokines, induction of factors that affect responsiveness to cytokines in the BM, or production of inhibitors of eosinophil development. Importantly, we show that the airway mucosal surface remotely controls eosinophil development to serve its local needs.

These studies show that IFN-γ has potent local and systemic effects through its actions on the airway epithelium. Studies of inhaled IFN-γ in humans show that the effects are compartmentalized in the respiratory tract (45). Mild asthmatics that received inhaled IFN-γ over 3 wk exhibited a reduction in airway eosinophils without evidence of an increase in proinflammatory markers (46). Thus, the local effects of inhaled IFN-γ that were observed in asthmatics may represent anti-inflammatory, IFN-γ-induced airway epithelial-specific responses, such as those that we report in this paper. These studies support a role for inhaled IFN-γ as adjunctive therapy in persistent eosinophilic asthma.

**Disclosures**

The authors have no financial conflicts of interest.

**References**


Figure S1
Figure S2
**Supplemental Figure Legends**

**Figure S1. Th2 cell activation in mice that received Th2 or Th1+Th2 cells.** WT (C57BL/6) mice received Th2 or Th1+Th2 cells and inhaled OVA. Th2 cell number and IL-13 were measured in BAL (n=4-5 mice/group). These data are representative of two independent experiments.

**Figure S2. CXCR3 does not mediate Th1 inhibition of Th2-induced airway eosinophilia.** Th1, Th2 or Th1+Th2 cells were transferred into WT (C57BL/6) or cxcr3-/- mice followed by inhaled OVA. Mean number of BAL eosinophils (±SEM) are shown (n=3/group). Data are representative of 2 experiments. * p<0.002 Th1+Th2 compared to Th2