STAT6 regulates natural helper cell proliferation during lung inflammation initiated by *Alternaria*

Taylor A. Doherty,1,2* Naseem Khorram,1* Jinny E. Chang,1,3 Hee-Kyoo Kim,1,4 Peter Rosenthal,1 Michael Croft,2 and David H. Broide1

1Department of Medicine, University of California, San Diego, California; 2Division of Immune Regulation, La Jolla Institute for Allergy and Immunology, La Jolla, California; 3Division of Allergy, Asthma and Immunology, Scripps Clinic, La Jolla, California; and 4Department of Internal Medicine, Kosin University College of Medicine, Busan, Korea

Submitted 24 May 2012; accepted in final form 31 July 2012

*D. H. Broide and T. A. Doherty contributed equally to this work.

Asthma exacerbations are a major cause of morbidity for patients with severe asthma. Sensitization and exposure to the fungal allergen *Alternaria alternata* is a risk factor for severity of asthma symptoms, including episodes of fatal/near-fatal attacks (4, 9, 22, 28, 30). The spores of *Alternaria* are known to be a source of outdoor allergens for sensitized individuals but have also recently been detected at high levels indoors (36). Dispersion of the spores during periods of warm dry weather has been associated with epidemic, severe asthma symptoms (4, 9, 22, 28, 32, 34). The unique associations with *Alternaria* and severe asthma exacerbations are intriguing, but the mechanisms responsible for the unique pathogenesis of *Alternaria* are not well understood.

Our previous studies demonstrated that *Alternaria* can induce an innate eosinophilia in the airway compared with other allergens that is dependent on STAT6 (7). The finding that different aeroallergens may induce unique innate responses is supported by a report that the house dust mite (HDM) *Der- maphagoides pteronyssinus* contains an accessory protein homolog of MD-2 that can specifically activate Toll-like receptor type 4 signaling (39). Aside from this, mechanisms whereby individual allergens can specifically activate the innate immune system are largely unknown.

Our current studies reveal that *Alternaria* specifically induces activation of natural helper cells (NHCs), an innate lymphoid population. Innate lymphoid cell types have recently been discovered and do not express known lineage markers (lineage-negative), including CD3, CD4, CD8, T cell receptor (TCR)-β, TCR8, CD5, CD19, B220, NK1.1, Tcr119, Gr-1, CD11c, and FcR1 (26, 27, 33). This combination of surface markers excludes B, T, natural killer (NK), and NK T (NKT) cells, as well as mast cells, basophils, granulocytes, dendritic cells, and macrophages. Moro et al. (26) were the first to identify a novel population of small round cells with a single nucleus and scant cytoplasm they termed “natural helper cells” (NHCs) that have the innate ability to express high levels of T helper (Th) type 2 (Th2) cytokines after exposure to proinflammatory cytokine IL-33 (26). Studies of lineage-negative lymphocytes have demonstrated their presence in mice in the gastrointestinal tract, mesenteric fat and lymph nodes, spleen, liver, bone marrow, and lung (3, 5, 24, 26, 27, 33, 44), while studies in humans have identified their presence in the gastrointestinal tract, lung, bronchoalveolar lavage (BAL), and nasal polyps (23, 24). There are a limited number of studies examining the role of lineage-negative lymphocytes in models of disease. In studies of influenza viral infection in mice associated with type 1 interferon and Th1 immune responses, a population of cells in the mouse lung that closely resemble NHCs that contribute to airway hyperreactivity, as well as tissue remodeling/repair, has been described (5, 24). Very recently, it was reported that lung NHCs contribute to papain- and *Alternaria*-induced airway inflammation and highlight the role of IL-33 in promoting Th2 cytokine production (2, 12, 15). These studies have largely focused on innate lymphoid cell cytokine responses or contribution to airway hyperreactivity (1, 16), but mechanisms that regulate the accumulation and proliferation of lung NHCs after allergen challenge are largely unknown.
In this study, we have examined whether *Alternaria*, an aeroallergen specifically associated with severe asthma, induces a unique innate immune response compared with other allergens. We were surprised to find that *Alternaria alternata*, but not *Aspergillus fumigatus*, the HDM *D. pteronyssinus*, or Candida albicans, induced a rapid increase in airway levels of IL-33, accompanied by IL-33 receptor (IL-33R)-positive lung NHC production of IL-5, IL-13, and the pro-remodeling/repair growth factor amphiregulin. NHCs in the lung and bone marrow of mice, as well as similar cells in allergic humans, constitutively expressed transcription factors [GATA-3 and E26 transcription-specific sequence-1 (ETS-1)] that could allow for rapid induction of Th2 cytokines. Surprisingly, NHC numbers and proliferation were reduced in lungs of STAT6-deficient (STAT6−/−) mice after a single challenge with *Alternaria*, despite strong GATA-3 expression. *Alternaria* did not induce eosinophilia in mice deficient in NHCs (IL-7 (IL-7R) receptor-deficient (IL-7R−/−) mice), and blocking the IL-33 receptor additionally inhibited the innate eosinophil response. Thus the ability of *Alternaria* to rapidly activate lung NHCs that express ETS-1 and GATA-3 and proliferate in a STAT6-dependent manner may contribute to *Alternaria*-associated severe asthma.

**MATERIALS AND METHODS**

*Mice.* Six- to 8-wk-old male and female C57BL/6, recombination-activating gene (RAG) type 2-deficient (RAG2−/−), IL-7R−/−, and STAT6−/− mice were obtained from Jackson Laboratories and bred in-house. The mice were challenged with a single intranasal dose (25 or 100 µg) of *A. alternata* extract (lot nos. 136056 and 177372; LPS = 0.11–0.12 ng) or PBS and euthanized 3 h, 6 h, 12 h, or 3 days later. In some experiments, mice received a single intranasal challenge of 100 µg of *D. pteronyssinus* HDM extract (lot no. 165197; LPS = 0.19 ng), *A. fumigatus* (lot no. 118033, LPS = 0.04 ng), or *C. albicans* (lot no. 111797 LPS = 0.006 ng) and euthanized 12 h later. All extracts were obtained from Greer Laboratories, and LPS was measured by *Limulus* assay (Lonza) and reported as nanograms per 100 µg with a conversion factor of 10 endotoxin units per nanogram. In selected experiments, mice received 25 µg of *Alternaria* extract on days 0, 3, 6, and 9 and euthanized 24 h later. For in vivo T1/ST2 blocking studies, wild-type (WT) B6 mice received intraperitoneal injections of 0.1 mg/ml of anti-T1/ST2 (clone DJ8, rat IgG1, MD Bioscience) and sample data were further analyzed with Flow Jo software (Tree Star). Purified NHC were obtained using a FACS Aria cell sorter (BD Biosciences).

**ELISA for BAL cytokines and serum IgE.** ELISA of BAL supernatant for IL-4, IL-5, IL-9, IL-13, IL-25, CCL11, CCL24, IFN-γ, and amphiregulin and serum for total IgE (BD Biosciences) was performed according to the manufacturer’s instructions and read with a microplate reader (model 680, Bio-Rad). All ELISA kits used for BAL studies were obtained from R & D Systems, except the kit for IL-9, which was obtained from Biologend.

**Flow cytometry.** Lung single-cell suspensions or BAL cells were first incubated with a monoclonal antibody to CD16/CD32 (24G.2) for 10 min to block Fc receptors. BAL and lung cells were stained with peridinin-chlorophyll-protein complex (PerCP)-conjugated CD45.2, phycoerythrin (PE)-conjugated Siglec-F, allphycocyanin (APC)-conjugated Gr-1, and FITC-conjugated CD11c (eBioscience). Lung cells were also stained with PerCP-conjugated CD45.2 (eBioscience) and biotinylated T1/ST2 (clone DJ8, MD Bioscience) followed by streptavidin-APC or -PE (eBioscience). Lineage staining was performed only with FITC antibodies, allowing for the exclusion of B, T, NK, and NKT cells, as well as mast cells, basophils, granulocytes, dendritic cells, and macrophages. Lineage antibodies included FITC-conjugated lineage cocktail (Biologend), CD11c (BD Biosciences), NKJ1.1 (eBioscience), CD4 (BD Bioscience), CD5 (BD Biosciences), CD8 (BD Bioscience), FcR1 (Biologen), TCRβ (BD Bioscience), TCRγδ (Biologen), and CD19 (Biologen). Lung cells were also stained with various combinations of APC-conjugated Thy1.2 (Biologen), c-Kit (eBioscience), CD44 (eBioscience), PE-conjugated Sca-1 (eBioscience), CD25 (BD Bioscience), CD127 (Biologen), IL-4Ro (BD Pharmingen), IL-13Rα1 (eBioscience), or Thy1.2 (eBioscience). Lung NHCs were defined as lineage-negative T1/ST2-positive lymphocytes or lineage-negative Thy1.2-positive lymphocytes. PE-conjugated IL-5 and IL-13 (eBioscience) were used for intracellular staining after fixation and permeabilization (BD Biosciences). In selected experiments, lung single-cell suspensions were incubated at 37°C for 3 h with Golgi-Plugg (BD Biosciences) prior to intracellular staining. ETS-1 and GATA-3 staining were performed using a FoxP3 staining kit (eBioscience) followed by addition of PE-conjugated GATA-3 (eBioscience) or ETS-1 (GeneTex) polyclonal rabbit antibody and then F(ab')2 donkey anti-rabbit IgG (eBioscience). Ki-67 staining was performed using a FoxP3 staining kit (eBioscience) followed by APC-conjugated Ki-67 (eBioscience). Surface staining for amphiregulin was performed with polyclonal goat anti-amphiregulin antibody (R & D Systems) followed by incubation with PE-conjugated donkey anti-goat IgG (Santa Cruz Biotechnolgy). Human peripheral blood mononuclear cells were incubated with Fc block and then stained with a combination of FITC-conjugated human lineage cocktail (BD Bioscience), biotin-conjugated chemotactic receptor of Th2 cells (CRTH2; Miltenyi), FITC-conjugated CD4, TCRγδ CD235a, FcR1, CD11b, and Alexa 647-conjugated CD127 (eBioscience) followed by ETS-1 and GATA-3 intracellular staining. Flow cytometry was performed with an Accuri C6 cytometer (BD Biosciences), and sample data were further analyzed with Flow Jo software (Tree Star). Purified NHC were obtained using a FACS Aria cell sorter (BD Biosciences).

**Immunostaining.** Mouse lungs were fixed by intratracheal instillation of 4% paraformaldehyde, embedded in paraffin, and cut into 3-µm-thick sections for immunostaining. The tissue sections were deparaffinized, rehydrated in graded alcohol, and encircled with a hydrophobic film (ImmEdge PEN, Vector Laboratories). For retrieval of antigens, slides were placed in 10 mM sodium citrate buffer (pH 6.0) at a subboiling temperature for 10 min. For phosphorylated EGF receptor (p-EGFR) staining, sections were digested with proteinase K (Sigma-Aldrich) at a final concentration of 40 µg/ml in PBS for 5 min. Sections were treated in 3% hydrogen peroxide in distilled water for 10 min to quench endogenous peroxidase activity. Nonspecific protein binding was blocked with 2% goat serum in PBS for 30 min. Primary antibodies were diluted in blocking buffer and incubated overnight at...
4°C at a final dilution of 1:200 for EGFR Ab and 1:25 for p-EGFR Ab, respectively. EGFR was detected using rabbit anti-human EGFR antibody (sc-03, Santa Cruz Biotechnology) directed against amino acid residues 1005–1016, which are identical to corresponding sequences in murine EGFR. p-EGFR was detected using rabbit anti-p-EGFR (Tyr845) antibody 2231 (Cell Signaling Technology) directed against phosphorylated Tyr845. After primary antibody binding, sections were washed with PBS and then incubated with biotinylated goat anti-rabbit IgG (2 μg/ml) followed by signal amplification using the Elite ABC method and 3,3′-diaminobenzidine chromogen according to the manufacturer’s protocols (Vector Laboratories). Sections were counterstained with hematoxylin and mounted with glycerol gelatin (Sigma). EGFR- and p-EGFR-positive epithelial cells were counted and divided by the number of total epithelial cells to obtain the number of positive cells per airway. Six airways per mouse and ≥100 total epithelial cells per airway were analyzed.

**RESULTS**

Alternaria specifically induces innate eosinophilia dependent on IL-33R. To determine the innate immune response to the fungal allergen Alternaria, naive mice were treated with a single challenge with Alternaria extract, and BAL was performed 3, 6, and 12 h later. BAL eosinophils accumulated as early as 3 h and continued to increase by 12 h after challenge (Fig. 1A). IL-33 is a proinflammatory cytokine implicated in promoting Th2-type responses that lead to eosinophilic lung inflammation, even in the absence of adaptive immune cells.
Alternaria induces Th2 cytokine production in IL-33R-expressing lung NHCs. As the recently described NHCs, a lineage-negative lymphocyte population, express the IL-33R (T1/ST2) and respond to IL-33 by production of Th2 cytokines (26), we next investigated if a similar population was activated in the lungs following Alternaria challenge. Lung cells from mice that received a single challenge of Alternaria or PBS were stained with a lineage cocktail that allows for exclusion of B, T, NK, and NKT cells, as well as mast cells, basophils, granulocytes, dendritic cells, and macrophages. CD45-positive lymphocytes were gated, and lineage-negative IL-33R (T1/ST2)-positive cells were identified (Fig. 3A). Cytospin preparations of sorted lineage-negative IL-33R-positive cells revealed lymphocyte morphology with scant cytoplasm. Nearly all the lineage-negative cells were IL-33R-positive and expressed Sca-1, c-Kit, IL-7R, Thy1.2, CD25, and CD44 (Fig. 3B). Expression of these markers is most consistent with previously described NHCs (26).

To determine whether lung NHCs produce the Th2 cytokines IL-5 and IL-13, we performed intracellular staining (Fig. 3C). WT mice were given one intranasal challenge with Alternaria or PBS, and lungs were processed for FACS analysis 3 h later. In PBS-challenged (control) mice, the percentage of IL-5- and IL-13-producing lung NHCs was increased compared with isotype control staining, suggesting that low levels of IL-5 and IL-13 production may be constitutive. Over one-third of the lung NHCs from Alternaria-challenged mice were IL-5- and/or IL-13-positive when measured ex vivo. Thus IL-5 and IL-13 production in lung NHCs is rapid and robust within a few hours of a single Alternaria exposure.

We further investigated whether NHC numbers and cytokine production were affected by multiple challenges with Alternaria. After four challenges over 9 days with Alternaria or...
PBS, NHC numbers increased nearly sevenfold in the lung in Alternaria-challenged mice (Fig. 3D). Intracellular IL-5 staining revealed that significantly more IL-5 was produced in NHCs from Alternaria-than PBS-challenged mice (Fig. 3D). BAL eosinophils and serum total IgE were also markedly elevated in mice challenged four times with Alternaria (Fig. 3E). Thus lung NHCs expand and continue to produce Th2 cytokines after multiple challenges with Alternaria.

Lung NHCs express GATA-3 and IL-5 independent of STAT6. The transcription factors ETS-1 and GATA-3 bind to the IL-5 and IL-13 promoters and can synergize for Th2 cytokine production (35, 37). We performed intracellular staining for NHC GATA-3 and ETS-1 expression in lungs and bone marrow of naive mice (Fig. 4A). In the lung, GATA-3 and ETS-1 were constitutively expressed in NHCs compared with the lineage-positive T1/ST2 population. The lineage-positive T1/ST2-positive cells in the lung express c-Kit highly (not shown) and are consistent with a mast cell population, as previously reported to also express T1/ST2 (25). Similarly, in the bone marrow of naive mice, GATA-3 and ETS-1 were also constitutively expressed in NHCs (Fig. 4B), suggesting that NHCs are primed from development in unchallenged mice for rapid Th2 cytokine production.

GATA-3 can be induced in STAT6-dependent and -independent manners (14, 31). We thus investigated whether GATA-3 expression in lung and bone marrow NHCs requires STAT6. Lung NHCs from WT and STAT6−/− naive mice were stained for GATA-3 and ETS-1 expression (Fig. 4C). We were surprised to find no significant difference in intracellular GATA-3 expression or IL-5 production in vivo. STAT6 regulates lung NHC proliferation and innate eosinophilia. As STAT6 has been reported to regulate proliferation of many cell types, we investigated whether STAT6 regulated numbers or proliferation of lung NHCs after Alternaria challenge. In WT mice, the number of lung NHCs increased sig-
nificantly 3 days after one challenge with *Alternaria* compared with the number of NHCs in naive mice and 12 h after challenge (Fig. 5A). In contrast, the total number of lung NHCs from STAT6−/− mice did not significantly increase 3 days after challenge (Fig. 5A). The receptors upstream of STAT6 signaling are IL-4R and IL-13R. To determine whether lung NHCs express IL-4R and IL-13R, which could induce NHC STAT6-mediated responses, we stained lung NHC for IL-4R and IL-13R from naive and *Alternaria*-challenged WT mice (Fig. 5B). We found that IL-4Rα and IL-13Rα1 were significantly upregulated by 3 days after one *Alternaria* challenge. This suggests that one challenge with *Alternaria* primes lung NHCs to respond to IL-4 and IL-13 for induction of STAT6-mediated signals and that accumulation of lung NHCs partially depends on STAT6.

To determine whether proliferation of STAT6−/− NHCs was impaired in vivo and possibly accounts for the decreased numbers in STAT6−/− mice after *Alternaria* challenge, we performed NHC Ki-67 nuclear staining (Fig. 5C). Lung NHCs from naive WT and STAT6−/− mice displayed a similar and low level of proliferation (Ki-67⁺ NHCs). At 3 days after a single challenge with *Alternaria*, the percentage of proliferating lung NHCs from WT mice increased over fivefold (Fig. 5C). In contrast, only a modest increase in proliferation was observed in STAT6−/− lung NHCs from challenged mice compared with NHCs from unchallenged mice. Concomitant with a reduction in number and proliferation of lung NHCs in STAT6−/− mice, BAL eosinophils were significantly reduced compared with WT mice (Fig. 5D). BAL CCL11 and CCL24 levels were also significantly decreased in *Alternaria*-challenged STAT6−/− compared with WT mice (Fig. 5E). Thus STAT6 regulates NHC number and proliferation and innate eosinophilia induced by a single *Alternaria* challenge in nonsensitized mice. Furthermore, the receptors (IL-4R and IL-13R) upstream of STAT6 are significantly upregulated on lung NHCs after one challenge, suggesting that lung NHCs become primed to respond to IL-4/IL-13, leading to activation of STAT6 signaling.

*Alternaria*-induced innate eosinophilia is absent in mice lacking lung NHCs. To determine whether the presence of lung NHCs was required for the innate Th2-type response to *Alternaria*, we challenged mice that lack lung NHCs (IL-7R−/−). IL-7R (CD127) is expressed by lung NHCs from WT mice (Fig. 3B). Signaling through IL-7R occurs through the common gamma chain (γc), which is required for the presence of NHCs in the abdominal fat-associated lymphoid clusters, as they are absent in γc-deficient, as well as IL-7R−/−, mice (26, 42). Lung NHCs were indeed absent in IL-7R−/− compared with
WT and RAG2−/− mice (Fig. 6A). Next, we administered a single intranasal challenge with *Alternaria* or PBS to WT, RAG2−/−, and IL-7R−/− mice and determined levels of eosinophils and IL-5 at 12 h. Compared with WT mice, *Alternaria*-challenged IL-7R−/− mice did not mount an innate eosinophilia, and BAL IL-5 levels were similar in *Alternaria*-challenged IL-7R−/− mice and PBS-challenged WT mice (Fig. 6B). As IL-7R−/− mice have severely reduced T and B cell compartments, in addition to impaired NHC development, we also examined NHC responses in RAG2−/− mice that lack T and B compartments but have normal NHC responses. RAG2−/− mice had significantly increased BAL eosinophilia and IL-5 levels compared with IL-7R−/− mice at 12 h (Fig. 6C). The percentage of eosinophils in single-cell suspensions from lungs was increased in WT and RAG2−/− mice as early as 3 h after challenge, whereas eosinophils were nearly absent in PBS and IL-7R−/− mice (Fig. 6D). The percent NHCs, BAL eosinophils, and IL-5 were detected at higher levels in RAG2−/− than WT mice. BAL neutrophils were not significantly different between WT, RAG2−/−, and IL-7R−/− mice challenged with *Alternaria* (not shown), suggesting that NHC and IL-7R contribute specifically to the innate eosinophilic response. Taken together, IL-7R is required for the presence of lung NHCs as well as innate lung eosinophilia and IL-5 production after *Alternaria* challenge.

*Alternaria* induces NHC amphiregulin expression and activation of EGFR signaling. In addition to production of Th2 cytokines, innate lymphoid cells in the lung have recently been reported to produce the growth factor amphiregulin during influenza infection in mice (24). Amphiregulin has been implicated in asthma pathogenesis mainly as a proremodeling/repair mediator that was elevated during acute exacerbations (10, 17, 30, 41, 45), but whether allergens can induce amphiregulin in vivo in the lung has not been reported. We measured amphiregulin levels in the airway 12 h after a single allergen challenge with *Alternaria, Aspergillus, Candida*, or *D. pteronyssinus* HDM and found significantly increased amphiregulin levels only in mice challenged with *Alternaria* (Fig. 7A). BAL levels of soluble amphiregulin were detectable as early as 3 h after challenge with *Alternaria* and increased further at 12 h. The receptor for amphiregulin is EGFR, which is expressed primarily in the airway epithelium and is phosphorylated upon activation by EGFR ligand binding (40). Immunostaining of lung sections of *Alternaria*- and PBS-challenged mice revealed similar expression of EGFR in both groups and localization to the airway epithelium (Fig. 7B). In contrast, p-EGFR staining...
was significantly increased in the airway epithelium from *Alternaria*-challenged mice compared with PBS-challenged mice. These data suggest that amphiregulin and activation of EGFR, the receptor for amphiregulin, are induced within 12 h after *Alternaria* challenge.

Amphiregulin is initially upregulated on the cell surface prior to cleavage into the soluble form. Lung NHC surface amphiregulin from PBS-challenged mice revealed minimal expression, but expression was significantly increased 6 h after *Alternaria* challenge (Fig. 7C). In contrast to Alternaria-challenged mice, we found no difference in lung NHC surface expression or BAL levels of amphiregulin after challenges with other extracts compared with PBS-challenged mice (Fig. 7D). We then measured NHC amphiregulin expression in STAT6−/− mice after *Alternaria* challenge and found a significant reduction in surface amphiregulin expression compared with Alternaria-challenged WT mice (Fig. 7E). This suggests that *Alternaria* promotes NHC Th2 cytokine production as well as expression of the pro-remodeling/repair growth factor amphiregulin, which is partially dependent on STAT6.

**Human lineage-negative CRTH2+/CD127+ lymphocytes express GATA-3 and ETS-1.** Limited reports are available that demonstrate the presence lineage-negative innate lymphoid cells in humans. A recent study demonstrated expression of the prostanlaidin D2 receptor CRTH2, a marker for human Th2 cells, on innate lymphoid cells in human peripheral blood and tissues (23). We investigated whether lineage-negative lymphocytes that were positive for CRTH2 and CD127 constitutively expressed the Th2 transcription factors GATA-3 and ETS-1. We found that lineage-negative CRTH2+/CD127+ lymphocytes in human peripheral blood from allergic individuals highly express GATA-3 and ETS-1 (Fig. 8A). As GATA-3 can be expressed in many cell types, including Th2 cells, we compared the percentage of GATA-3-expressing cells in the lineage-negative CRTH2+/CD127+ lymphocyte population with lineage-positive CD127+CRTH2+ populations (Fig. 8B). Very little GATA-3 was expressed in the lineage-positive CD127+ population, whereas >50% of lineage-negative CD127+ cells expressed GATA-3. Approximately 30% of lineage-negative CRTH2+ cells expressed GATA-3 compared with 60% of the lineage-negative CRTH2+ cells. This suggests higher expression of GATA-3 in CRTH2+CD127+ lineage-negative lymphocytes in the blood of allergic individuals than in the respective lineage-positive populations. Overall, transcription factors involved in IL-5 and IL-13 production were constitutively expressed in lung and bone marrow NHCs in mice, as well as in peripheral blood CRTH2+ lineage-negative lymphocytes in humans, suggesting that NHCs are primed from development for Th2 cytokine production in mice and humans.

**DISCUSSION**

Our studies demonstrate that *Alternaria*, an allergen specifically associated with severe asthma exacerbations (4, 9, 22, 28, 29, 32, 34), can activate NHCs to produce the Th2 cytokines IL-5 and IL-13, as well as upregulate the expression of IL-4R and IL-13R and the pro-remodeling/repair growth factor amphiregulin, which is elevated during asthma exacerbations (10, 17, 30, 41, 45). In addition, we demonstrated an important role for STAT6 in NHC proliferation, but not Th2 cytokine production, suggesting that the alternate transcription factors (GATA-3 and ETS-1) we identified to be expressed constitutively in mouse and human NHCs may play a more important role than STAT6 in rapid innate Th2 cytokine responses to *Alternaria*. In contrast to the very important role of STAT6 in Th2 cytokine production by lineage-positive conventional T cells, lineage-negative NHC production of Th2 cytokines occurred independent of STAT6.

Innate lymphoid cell types that produce large amounts of the Th2 cytokines IL-5 and IL-13 after IL-33 stimulation have only recently been described (26, 27, 33). Lung innate lymphoid cells are activated during influenza viral infection and contrib-
ute to airway hyperresponsiveness and tissue repair (5, 24). Our studies suggest that the fungal allergen *Alternaria* can specifically induce high levels of IL-33 and activate NHCs in the lung to produce Th2 cytokines. Influenza and other respiratory viruses can precipitate severe/life-threatening asthma exacerbations, similar to *Alternaria* exposure in some cases (4, 29, 32, 34), suggesting that NHC activation may be a link in asthma exacerbation.

We compared the innate response to *Alternaria* extract with the response to other allergens and found that *Alternaria* specifically induced high levels of IL-33 in the airway compared with *Aspergillus*, *Candida*, and *D. pteronyssinus* HDM. A previous report demonstrated that *Alternaria* induced airway IL-33 release that was dependent on the danger signal extracellular ATP (20), but comparative studies with other allergens in vivo have not been reported. The same group very recently showed that innate lymphoid cells in the lung mediate the eosinophilic response after three *Alternaria* challenges over 6 days (2). Our findings extend the important role of lung NHCs in the eosinophilic airway response to even earlier time points (within 12 h) and after only one challenge with *Alternaria*. The innate eosinophilia induced by *Alternaria* was abrogated by IL-33R blockade, suggesting that IL-33-induced NHC activation is the dominant mechanism after *Alternaria* challenge, although other direct or indirect mechanisms of NHC activation may be present. The finding that different aeroallergens may induce unique innate responses is supported by a report that the HDM *D. pteronyssinus* contains an accessory protein homolog of MD-2 that can activate Toll-like receptor 4 signaling (39). Our data suggest that *Alternaria* may specifically or more robustly direct innate responses through an IL-33/NHC pathway compared with other allergens, including HDM.

We found that NHCs in the lung and bone marrow from unchallenged mice constitutively express the transcription factors GATA-3 and ETS-1, which can synergistically induce Th2 cytokine transcription (35, 37). A recent study demonstrated that GATA-3 was required for accumulation of IL-13-producing innate Th2 cells in the lungs after helminth infection, suggesting that GATA-3 does regulate innate lymphoid cells in the lung (21). The finding that NHCs in the bone marrow of mice, and a similar population in human blood, express GATA-3 and ETS-1 suggests that the cells are primed from development for rapid and robust Th2 cytokine production. This notion is supported by a recent report showing that a similar lineage-negative T1/ST2-positive population in the bone marrow is responsive to IL-33 and produces IL-5 and IL-13 (3). The aim of our studies of NHCs in human blood was to determine whether ETS-1 and GATA-3 are constitutively expressed. Future investigation is required to determine whether there are differences in NHC numbers or responses...
between patients with allergic rhinitis and healthy controls or patients with asthma.

The transcription factor GATA-3 can be induced in STAT6-dependent and -independent manners (14, 31). We found that lung NHC GATA-3 expression was not reduced in STAT6−/− mice, suggesting that lung NHCs maintain GATA-3 expression in a STAT6-independent manner. In Th2 cells, IL-4 and IL-13 signaling activates STAT6 and GATA-3 to promote Th2 cytokine production and Th2 differentiation (13). Our findings of similar GATA-3 expression and IL-5 production from STAT6−/− lung NHCs suggest a differential regulation of Th2 cytokine production in NHCs compared with Th2 cells that are largely STAT6-dependent.

Interestingly, we detected a reduction in NHC numbers and proliferation in the lungs of STAT6−/− mice after one challenge with Alternaria compared with WT mice, suggesting a novel role for STAT6 in the regulation of NHCs. This finding is consistent with a recent report showing that STAT6 regulated the total numbers of innate Th2 cells in the lungs of mice, suggesting that lung NHCs maintain GATA-3 expression in a STAT6-independent manner. In Th2 cells, IL-4 and IL-13 signaling activates STAT6 and GATA-3 to promote Th2 cytokine production and Th2 differentiation (13). Our findings of similar GATA-3 expression and IL-5 production from STAT6−/− lung NHCs suggest a differential regulation of Th2 cytokine production in NHCs compared with Th2 cells that are largely STAT6-dependent.

We found that Alternaria induces amphiregulin in the airway and on NHCs in the lung and induces activation of EGFR, the receptor for amphiregulin in bronchial epithelium. Thus lung NHC amphiregulin expression in response to Alternaria challenge is associated with activation of its receptor on airway epithelium, suggesting a mechanism for NHC to modulate epithelial cell function in asthma. Amphiregulin has been found to be elevated in asthma patients during exacerbations and may contribute to airway remodeling features, including mucus production (10, 17, 30, 41, 45). Importantly, a recent report showed that amphiregulin was highly expressed in microarray studies of sorted innate lymphoid cells in the lung compared with lymphoid tissue inducer cells in the spleen of naive mice (24). In vivo administration of recombinant amphiregulin after influenza viral infection led to improved tissue repair in mice.
depleted of innate lymphoid cells, suggesting that amphiregulin has a protective role. In contrast, in vitro studies (10, 30, 41, 45) suggest that amphiregulin may contribute to pathological remodeling responses. The precise role of amphiregulin in protecting or contributing to airway remodeling in asthma requires further investigation, although a novel finding from our studies is that NHC surface amphiregulin is significantly upregulated after Alternaria challenge and is partially dependent on STAT6.

In summary, our studies demonstrate the novel finding that Alternaria, an allergen specifically associated with severe asthma exacerbations, induces an innate NHC-mediated rapid burst of Th2 cytokine (IL-5 and IL-13) production, as well as expression by NHCs of IL-4R, IL-13R, and amphiregulin, and initiates eosinophilic inflammation compared with other allergens such as Aspergillus, D. pteronyssinus HDM, or Candida. In addition, we have demonstrated an important role for STAT6 in NHC proliferation, but not Th2 cytokine production, suggesting that alternate transcription factors (GATA-3 and STAT6) we identified to be expressed constitutively in mouse and human NHCs may play a more important role than STAT6 in rapid innate Th2 cytokine responses to Alternaria. In contrast to the very important role of STAT6 in Th2 cytokine production by lineage-positive conventional T cells, lineage-negative to the very important role of STAT6 in Th2 cytokine production.

The ability of Alternaria to rapidly induce IL-33, as well as the constitutive expression by NHCs of GATA-3 and ETS-1, may contribute significantly to a rapid Th2 innate response that could trigger asthma exacerbations.

GRANTS

This study was supported by National Institute of Allergy and Infectious Diseases Grant 1K08 AI-080938 (to T. A. Doherty) and Grants AI-38425, AI-70535, and AI-72115 (to D. H. Broide).

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

T.A.D., N.K., M.C., and D.H.B. are responsible for conception and design of the research; T.A.D., N.K., J.E.C., H.-K.K., and P.R. performed the experiments; T.A.D., N.K., J.E.C., H.-K.K., and P.R. analyzed the data; T.A.D., N.K., J.E.C., H.-K.K., P.R., and D.H.B. interpreted the results of the experiments; T.A.D., N.K., and J.E.C. prepared the figures; T.A.D. and N.K. drafted the manuscript; T.A.D., N.K., M.C., and D.H.B. edited and revised the manuscript; T.A.D. and N.K. approved the final version of the manuscript.

REFERENCES


L587

25. Moritz DR, Rodewald HR, Gheyselinck J, Klemenz R. The IL-1 receptor-related T1 antigen is expressed on immature and mature mast


