TH17 Cells Mediate Steroid-Resistant Airway Inflammation and Airway Hyperresponsiveness in Mice

Laura McKinley, John F. Alcorn, Alanna Peterson, Rachel B. DuPont, Shermaaz Kapadia, Alison Logar, Adam Henry, Charles G. Irvin, Jon D. Piganelli, Anuradha Ray and Jay K. Kolls

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Steroid-resistant asthma comprises an important source of morbidity in patient populations. TH17 cells represent a distinct population of CD4+ T cells that mediate neutrophilic inflammation and are characterized by the production of IL-17, IL-22, and IL-6. To investigate the function of TH17 cells in the context of Ag-induced airway inflammation, we polarized naive CD4+ T cells from DO11.10 OVA-specific TCR-transgenic mice to a TH2 or TH17 phenotype by culturing in conditioned medium. In addition, we also tested the steroid responsiveness of TH2 and TH17 cells. In vitro, TH17 cytokine responses were not sensitive to dexamethasone (DEX) treatment despite immunocytochemistry confirming glucocorticoid receptor translocation to the nucleus following treatment. Transfer of TH2 cells to mice challenged with OVA protein resulted in lymphocyte and eosinophil emigration into the lung that was markedly reduced by DEX treatment, whereas TH17 transfer resulted in increased CXC chemokine secretion and neutrophil influx that was not attenuated by DEX. Transfer of TH17 or TH2 cells was sufficient to induce airway hyperresponsiveness (AHR) to methacholine. Interestingly, AHR was not attenuated by DEX in the TH17 group. These data demonstrate that polarized Ag-specific T cells result in specific lung pathologies. Both TH2 and TH17 cells are able to induce AHR, whereas TH17 cell-mediated airway inflammation and AHR are steroid resistant, indicating a potential role for TH17 cells in steroid-resistant asthma.


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1 Address correspondence and reprint requests to Dr. Jay K. Kolls, Children’s Hospital of Pittsburgh, Suite 3765, 3705 Fifth Avenue, Pittsburgh, PA 15213. E-mail address: jay.kolls@chp.edu
2 Abbreviations used in this paper: AHR, airway hyperresponsiveness; Ad, adenovirus; BAL, bronchoalveolar lavage; DEX, dexamethasone; GR, glucocorticoid receptor; i.t., intratracheal; LH, lung homogenate; KO, knockout; rm, recombinant mouse; WT, wild type; PMN, polymorphonuclear neutrophil; PAS, periodic acid-Schiff.

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transfer of polarized T cell populations to SCID mice (16). SCID mice were chosen to isolate the contribution of the transfected cells as opposed to contaminating endogenous CD4+ T cell populations. Additionally, this model does not use adventitious priming in vivo which has recently been questioned in terms of its relevance to airway sensitization, which is what occurs in human allergen sensitization.

Presently, we report that in vitro-polarized T(H)17 cells are non-responsive to glucocorticoids. Adoptive transfer of these cells in a model of Ag-induced airway inflammation resulted in increased CXC chemokine secretion and G-CSF in the lung that was associated with neutrophil influx to the airways. Treatment of T(H)17 cell-reconstituted mice with dexamethasone (DEX) did not alter airway inflammation but did attenuate T(H)2-induced airway inflammation. Reconstitution of mice with either T(H)2 or T(H)17 cells resulted in increased AHR to methacholine challenge. Surprisingly, DEX treatment significantly reduced AHR in mice that received T(H)2 cells but not in T(H)17-reconstituted animals. These data demonstrate the significance of T(H)17 cellular responses in airway disease and implicate these cells as having a role in steroid-resistant asthma.

Materials and Methods

Mice
Six- to 8-wk-old, male BALB/c mice and SCID mice were purchased from The National Cancer Institute. C.D011.10 TCR-transgenic mice were obtained from The Jackson Laboratory. IL-17R null mice have been previously described (17). All animals were housed in a pathogen-free environment and given food and water ad libitum. All experiments were approved by the Children’s Hospital of Pittsburgh Animal Research and Care Committee.

Abs and reagents

Cell culture. Recombinant mouse (rm) IL-2, rmIL-4, rmIL-6, rmIL-23, porcine TGF-β1, anti-mouse IL-4 (clone 30340.11), and anti-mouse IFN-γ (clone 37895) were purchased from R&D Systems.

Immunofluorescence. Rabbit anti-mouse glucocorticoid receptor (GR; Affinity BioReagents) and goat anti-rabbit IgG conjugated to Alexa Fluor 555 (Invitrogen) were used.

Western blot. Polyclonal rabbit anti-mouse GR (Affinity BioReagents), mouse monoclonal anti-β-actin (Santa Cruz Biotechnology), goat anti-rabbit IgG conjugated to alkaline phosphatase (AP; Bio-Rad), and goat anti-mouse IgG conjugated to AP (Santa Cruz Biotechnology) were used.

In vitro differentiation of Th cell subsets

CD4+ T cells from the spleens and lymph nodes of C.D011.10 TCR-transgenic mice were enriched by negative selection using magnetic beads (Miltenyi Biotec). CD4+CD62L−CD25+ cells were sorted on a FACSAria (BD Biosciences); purity was consistently 99%. Cells were cultured with irradiated APCs pulsed with OVA peptide 323–339 (OVA323–339) under polarizing conditions as previously reported (18). Briefly, medium was supplemented with 20 U/ml IL-2, 5 ng/ml rmIL-4, and 10 µg/ml anti-IFN-γ (for T(H)2 polarization), or 10 ng/ml rmIL-23, 1 ng/ml TGF-β2, 20 ng/ml rmIL-6, 10 µg/ml anti-IL-4, and anti-IFN-γ (for T(H)17 polarization). Cultures were split 1:2 on day 3 and harvested on day 6. The total number of cells was determined by counting on a hemocytometer; viable cells were defined by trypan blue exclusion. APCs alone were CD4bright or CD4dim and proliferating CD4+ T cells were CD4bright and stained positively with KJ-126 (eBioscience) and anti-Do11.10.1C11 TCR Ab. CD4bright cells were selected for immunohistochemistry studies.

In vitro assays

To confirm the phenotype of the Th cell subsets, cells were stimulated with in vitro with PMA/ionomycin for ELISPOT assays (R&D Systems) or anti-CD3/anti-CD28-coated microbeads (Dynal) for cytokine assays. Where indicated, cells were pretreated with increasing doses of DEX (Sicor Pharmaceuticals) for 2 h before the addition of microbeads. After 36 h in culture, cell supernatants were collected and stored at −80°C until analysis. To measure NFAT activity of polarized T cells, primary culture mouse T cells (1 × 10⁶/ml) were transfected with 4 µg of NFAT-luciferase plasmid (gift from S. Gaffen, State University of New York, Buffalo, NY) and 1 µg of SV40-RENilla. Transfection was conducted with the Mouse T Cell Nucleofector Kit (Amaxa Biosystems) using the X-005 program on the Nucleofector II instrument (Amaxa Biosystems). Following transfection, T cells were cultured for 18 h and treated with or without 1 µM DEX for 2 h before treatment with anti-CD3/anti-CD28-coated Dynabeads (Invitrogen Dynal) for 6 h at 37°C. After stimulation, luciferase activity was determined using the Dual-luciferase Reporter Assay System (Promega). NFAT-luciferase levels were normalized to SV40-RENilla as an internal transfection control.

Immunocytochemistry

Superfrost Plus Micro Slides (VWR International) of 100,000 cells CD4+ cells (selected by Miltenyi beads) were fixed in 100% ice-cold methanol for 10 min. Slides were stained with rabbit anti-mouse GR and visualized with goat anti-rabbit IgG conjugated to Alexa Fluor 555 (Invitrogen) as previously described (19). Accumulation of GR in the nucleus was observed by epifluorescence illumination with a Zeiss AxioPlan 2 microscope equipped with a ×63, 1.4 aperture oil immersion objective. Quantification of fluorescence was performed by analyzing regions of interests (drawn over the 4′,6-diamidino-2-phenylindole nuclear signal) of 100 cells captured with a charge-coupled device camera (Intelligent Imaging Innovations) and relative intensity values were determined and averaged with SlideBook software (Intelligent Imaging Innovations).

Western blot analysis

Nuclear and cytoplasmic protein fractions were extracted from differentiated T cells after DEX treatment using the Nuclear Extract Kit (Active Motif) according to the manufacturer’s instructions. Protein concentration was determined using a BCA Protein Assay Kit (Pierce Biotechnology). AP development was visualized by the AP Conjugate Substrate Kit (Bio-Rad) according to the manufacturer’s instructions.

Adoptive transfer model

BALB/c SCID mice were challenged with OVA protein (50 µg/mouse, intratracheal (i.t.); Sigma-Aldrich) on day 1. On day 0, 1 × 10⁶ differentiated Th cells were adoptively transferred by retro-orbital injection. Mice were challenged with OVA for 3 consecutive days after cell transfer (50 µg/mouse/day, i.t.). Animals were sacrificed 24 h after the last airway challenge. Where indicated, mice were treated with 2.5 mg/kg DEX or PBS control 2 h before cell transfer on day 0 and before OVA challenge on day 2. In separate experiments, wild-type (WT) BALB/c mice and IL-17R null mice on a BALB/c background underwent the same adoptive transfer and OVA challenge protocol.

Bronchoalveolar lavage (BAL) fluid and lung tissue collection

Lungs were lavaged with five 1-ml volumes of calcium- and magnesium-free PBS. The supernatant from the first 1-ml aliquot was stored at −80°C for later analysis. Cell pellets from both aliquots were pooled in 1 ml and total white blood cells in BAL fluid were counted using a particle counter (Z1; Beckman Coulter). Cytospins of 100,000 cells were prepared using a Shandon Cytospin 4 (Thermo Electron), slides were stained with HEMA 3 (Fisher Scientific), and differentials were quantified by counting 100 cells. Lungs were harvested following the collection of lavage fluid. The right lungs were homogenized in 1 ml of PBS containing 0.05% Triton X-100 and Complete Protease Inhibitor (Roche). Homogenate was centrifuged at 12,000 × g for 15 min and supernatant was stored at −80°C for later cytokine analysis.

Cytokine analysis

Cell supernatants, BAL fluid, and lung homogenate (LH) samples were analyzed for protein levels of G-CSF, IL-4, IL-5, IL-6, IL-13, IL-17, IFN-γ, and KC using a Luminex multiplex suspension cytokine array (Linclo) according to the manufacturer’s instructions. The data were analyzed using Bio-Plex Manager software (Bio-Rad). IL-22 was measured using a commercial ELISA (R&D Systems) following instructions provided by the manufacturer.

Overexpression of IL-4 and IL-17 in the lungs

Adenovirus expressing IL-4, IL-17, or luciferase as a control was given at 10⁷ PFU i.t. on day 0 and AHR was determined 72 h later. Overexpression of IL-4, IL-13, and IL-17 was determined by Luminex in both the BAL fluid and LH of recipient mice.
**FIGURE 1.** TH17 cells are not sensitive to DEX treatment in vitro. CD4+CD62L+CD25− naive T cells isolated from DO11.10 OVA TCR-transgenic mice were cultured with WT BALB/c splenocytes that had been pulsed with OVA323−339 under polarizing conditions. On day 6, cells were collected and stimulated with PMA/ionomycin for precursor frequency by ELISPOT or pretreated for 2 h with the indicated doses of DEX before stimulation with CD3/CD28 microbeads; beads indicates untreated T cells stimulated with CD3/CD28 microbeads; beads indicates untreated T cells stimulated with CD3/CD28 microbeads; μM DEX + bead indicates T cells pretreated with the indicated dose of DEX and stimulated with CD3/CD28 microbeads. Cell culture supernatant was collected at 36 h after stimulation and the levels of TH2 cytokines were determined by multiplex suspension array assay. A, IL-4 levels from TH2 cells. B, IL-13 levels from TH2 cells. C, IL-5 levels from TH2 cells. D, IL-13 levels from TH2 cells. E, IL-17 levels from TH2 cells. F, IL-22 levels from TH17 cells. All data are graphed as mean ± SEM for n = 5–8; s, p < 0.01.

**Determination of AHR**

Airway responsiveness to methacholine challenge was determined on day 4 as previously described using anesthetized, intubated mice connected to a computer-controlled small-animal mechanical ventilator (flexivent; SCI-REQ) (20). Airway resistance values (Rn) were calculated in response to progressive concentrations of methacholine administered by i.v. injection.

**Statistical analysis**

Data are reported as mean ± SEM. GraphPad Prism version 4.0 was used to calculate p values using one-way ANOVA with a Tukey multiple comparison posttest. A value of p < 0.05 was considered statistically significant.

**Results**

**TH17 cells are resistant to DEX treatment in vitro**

Studies have shown that glucocorticoids inhibit the production of IL-4, IL-5, and IL-13 from TH2 cells (21). To test the sensitivity of TH17 cells to glucocorticoids, naive CD4+ T cells from DO11.10 TCR-transgenic mice were differentiated in the presence of IL-6, IL-23, TGF-β, anti-IL-4, and anti-IFN-γ (18). As a positive control, naive CD4+ T cells were polarized toward a TH12 phenotype by conditioning with IL-2, IL-4, and anti-IFN-γ. After 6 days in culture, polarization was confirmed by PMA/ionomycin stimulation and ELISPOT analysis (Fig. 1, A and B) and secreted cytokine analysis (Fig. 1, C–F). Only TH17 cells produced IL-17 (Fig. 1A), whereas in TH2 cells the precursor frequency of IL-4-producing T cells was 5.6-fold greater in TH2 cells compared with T cells grown in TH17 conditions (Fig. 1B). Cells were also harvested on day 6 and treated with increasing doses of DEX for 2 h before stimulation with anti-CD3/anti-CD28-coated microbeads.

As expected, TH12 cells secreted IL-4 (data not shown), IL-5, and IL-13 following CD3/CD28 stimulation and TH17 cells secreted high levels of IL-17 and IL-22 following CD3/CD28 stimulation and EL-17 processing, or pretreated for 6 h with the indicated doses of DEX before stimulation with CD3/CD28 microbeads; beads indicates untreated T cells stimulated with CD3/CD28 microbeads; μM DEX + bead indicates T cells pretreated with the indicated dose of DEX and stimulated with CD3/CD28 microbeads. Cell culture supernatant was collected at 36 h after stimulation and the levels of TH2 cytokines were determined by multiplex suspension array assay. A, IL-4 levels from TH2 cells. B, IL-13 levels from TH2 cells. C, IL-5 levels from TH2 cells. D, IL-13 levels from TH2 cells. E, IL-17 levels from TH2 cells. F, IL-22 levels from TH17 cells. All data are graphed as mean ± SEM for n = 5–8; s, p < 0.01.

**DEX treatment inhibits Ag-specific TH17-mediated airway inflammation but not TH17-mediated airway inflammation in an adoptive transfer model**

To determine the Ag-specific immune response elicited by effector TH17 cells in vivo, an adoptive transfer model of airway Ag-induced inflammation was used (Fig. 2A). In vitro-polarized TH17 cell subsets were transferred i.v. to SCID mice on a BALB/c background that had been challenged with OVA protein i.t. 1 day before cell transfer to promote cell migration to the airways (16). Following cell transfer, mice were challenged with OVA i.t. for 3 consecutive days and sacrificed on day 4, 24 h after the last OVA challenge. Mice were treated with DEX (2.5 mg/kg) or PBS control by i.p. injection 2 h before cell transfer on day 0 and again 2 h before OVA challenge on day 2. Control mice reconstituted with TH2 cells that were challenged with OVA had increased levels of IL-5 and IL-13 in LH (Fig. 2, B and C). Mice transferred TH2 cells without OVA challenge or scid mice challenged with OVA without T cell transfer had LH levels of IL-5 and IL-13 that were <50

**As expected, TH12 cells secreted IL-4 (data not shown), IL-5, and IL-13 (Fig. 1, C and D)** following CD3/CD28 stimulation and TH17 cells secreted high levels of IL-17 and IL-22 (Fig. 1, E and F). Although both IL-5 and IL-13 generation from TH17 cells were inhibited at all doses of DEX studied, TH17 cell cytokine production was not sensitive to DEX treatment at any dose tested. Apoptosis was analyzed by annexin V and 7-aminoactinomycin D staining and >85% of the TH2 and TH17 cells were annexin V and 7-aminoactinomycin negative (viable) after 1 μM DEX treatment (data not shown).
Treatment with DEX significantly inhibited the lung levels of IL-5 and IL-13 (Fig. 2, B and C). Groups reconstituted with T$_{H}17$ cells showed an increase in IL-17, G-CSF, and the mouse homolog of CXCL8 KC in LH that was not observed in mice receiving T$_{H}2$ cells (Fig. 2, D–F). Mice transferred T$_{H}17$ cells without OVA challenge or scid mice challenged with OVA without T cell transfer had LH levels of IL-17 and G-CSF that were <100 pg/ml; KC levels were <500 pg/ml in these control mice (data not shown). Concurrent with the in vitro glucocorticoid resistance, DEX treatment did not attenuate the T$_{H}17$-induced inflammatory cytokine response; in fact, there was a trend toward increased levels of KC in the LH of DEX-treated T$_{H}17$-reconstituted mice compared with the T$_{H}17$ PBS control.

Transfer of either T$_{H}12$ or T$_{H}17$ cells resulted in specific cellular influx into the airways. We initially assessed lymphocyte recruitment into the lung 24 h after adoptive transfer. Both transfer of T$_{H}12$ cells and T$_{H}17$ cells resulted in 0.15 ± 0.06 × 10$^6$ and 0.18 ± 0.07 × 10$^6$ CD3/CD4$^+$ cells in BAL (p = NS). However, after three challenges with OVA, differential counting of BAL fluid cytospins showed that T$_{H}12$ reconstitution resulted in airway inflammation consisting of both eosinophils and lymphocytes and to a lesser extent polymorphonuclear neutrophils (Fig. 3, A–C). Mice transferred T$_{H}12$ cells without OVA challenge or scid mice challenged with OVA without T cell transfer had BAL eosinophil counts that were <0.1 × 10$^6$/ml (data not shown). The influx of lymphocytes and eosinophils was highly sensitive to DEX (Fig. 3, A and B), whereas the small numbers of polymorphonuclear neutrophils in the BAL were not inhibited by DEX treatment (Fig. 3 C). As expected, T$_{H}17$ transfer resulted in a primarily neutrophilic airway response (Fig. 3 C). Mice transferred T$_{H}17$ cells without OVA challenge or scid mice challenged with OVA without T cell transfer had BAL neutrophil counts that were <0.2 × 10$^6$/ml (data not shown). In contrast to mice receiving T$_{H}12$ cells, DEX treatment exacerbated airway neutrophilia in T$_{H}17$-reconstituted mice.

To determine whether the airway responses of reconstituted mice were mediated by IL-17 per se or another product of T$_{H}17$ cells, we adoptively transferred T$_{H}17$ cells into IL-17R KO mice.
on a BALB/c background and challenged them with OVA 1 day before and for 3 consecutive days after cell transfer as before (Fig. 2A). *IL-17R* KO mice had significantly attenuated KC, G-CSF, and IL-6 responses compared with WT BALB/c controls (Fig. 4, A–C). Consistent with the decrease in CXC chemokine production in *IL-17R* KO mice, there was a significant decrease in the number of neutrophils in the airways (Fig. 4D). Again, there was not a significant increase in eosinophil recruitment to the lung in either WT or IL-17R KO mice transferred T\(_{H17}\) cells and challenged with OVA (Fig. 4E). These data indicate that the inflammatory cytokine response and cellular influx associated with T\(_{H17}\) cell transfer in this model system is mediated primarily by IL-17 signaling through the IL-17R.

**Ag-induced AHR following adoptive transfer of T\(_{H17}\) cells is not attenuated by DEX treatment**

Having established the airway inflammation induced by T\(_{H17}\) cell transfer, we wanted to determine whether T\(_{H17}\) cells are sufficient to induce mucus hyperplasia and AHR at a level comparable to

![Image of Figure 3](http://www.jimmunol.org/)

**FIGURE 3.** T\(_{H2}\) and T\(_{H17}\)-mediated airway inflammation and AHR. BAL fluid differential was determined by counting at least 100 cells from cytospins prepared of 100,000 cells. Data for A, lymphocytes; B, eosinophils; C, neutrophils; and D, macrophages are graphed as mean ± SEM percentage of total cells for n = 4–6; *, p < 0.05 PBS vs DEX in same transfer group; #, p < 0.05 T\(_{H2-PBS}\) vs T\(_{H17-PBS}\).

![Image of Figure 4](http://www.jimmunol.org/)

**FIGURE 4.** The inflammatory response associated with T\(_{H17}\) cell transfer is mediated by IL-17. T\(_{H17}\) cells were transferred to *IL-17R* KO mice and BALB/c controls that had been challenged with OVA 1 day before transfer. Mice were challenged with 50 μg of OVA per mouse for 3 consecutive days after transfer. BAL fluid differential and LH levels of cytokines and chemokines 24 h after the last airway challenge were determined. Levels of KC (A), G-CSF (B), and IL-6 (C) in the LH were determined by multiplex suspension cytokine array. BAL fluid neutrophils (D), and eosinophils (E) are expressed as cells/ml × 10\(^6\). Data are graphed as mean ± SEM for n = 4–6; *, p < 0.05 compared with WT control.
that observed following transfer of Th2 cells. A significant hallmark of allergic airway disease is mucus hyperplasia; to address this, LH expression of gob5 was determined by real-time PCR. Data are normalized to control mice that had been challenged with OVA on days 1, 1, 2, and 3 but received a mock PBS transfer on day 0. TH2 transfer resulted in a marked significant increase in gob5 gene expression in the lung (Fig. 5A), which was decreased in the DEX treatment group (Fig. 5B). Expression of gob5 in TH17 cell transfer groups was also significantly elevated over mock-transferred animals (200-fold increase compared with OVA-challenged mice without cell transfer) but was ~10-fold lower than that of the TH2 transfer groups (Fig. 5A). However, compared with the TH2 transfer groups, DEX treatment had no effect on gob5 gene expression in the TH17 cell transfer group. Expression of gob5 was confirmed by periodic acid-Schiff (PAS) staining of lung sections; Fig. 5B is representative sections from TH2 and TH17, transferred animals. Both TH2 and TH17 transfer groups exhibit positive PAS staining in airway epithelial cells.

To date, there are no data to demonstrate whether Th17 cells are sufficient to induce AHR. IL-17 levels in the sputum correlate with AHR to methacholine in asthmatic and chronic bronchitis patients (11). To determine whether IL-17 was sufficient to induce AHR, an adenovirus (Ad) overexpressing IL-17 (AdIL-17) was administered i.t. to WT BALB/c mice and AHR to methacholine was measured 72 h later. As controls, separate
groups of mice were given an adenovirus overexpressing luciferase (Adluc) or IL-4 (AdIL-4) which induces local IL-13 and IL-5 concentrations in AdIL-4-treated mice was 358 ± 68 pg/ml vs 5.6 ± 2.2 in Adluc-treated mice). Overexpression of IL-4 or IL-17 in the lung was sufficient to cause significant increases in airway resistance in response to methacholine challenge (Fig. 5C). AdIL-4 caused a greater shift in the methacholine dose-response curve with significantly higher airway resistance (Rn) values in mice administered the mid-range dose of 12.5 mg/ml. At the 6.25-mg/ml dose and the 25-mg/ml dose, there was no significant difference between AdIL-4 and AdIL-17, but both were significantly higher than Adluc control mice. These data that show IL-17 overexpression is sufficient to induce AHR to methacholine in WT mice.

We next examined the AHR mediated by Th17 cells in the adoptive transfer model of Ag-specific airway inflammation (Fig. 2A). AHR to methacholine was determined 24 h after the last airway challenge. Fig. 5D depicts the dose response of methacholine in control mice, mice that received Th2 cells treated with vehicle, or mice transferred Th2 cells treated with DEX. Ag-challenged mice that received Th2 cells and vehicle treatment showed a significant leftward shift of the methacholine dose-response curve compared with Ag-challenged control mice that did not receive T cells (Fig. 5D). This shift was significantly attenuated with DEX treatment (Fig. 5D).

**Mechanism of enhanced Th17 cellular responses to DEX treatment**

Glucocorticoids exert their effects through binding the GR, resulting in nuclear translocation and transactivation of genes containing glucocorticoid-response elements (12). To determine whether Th17 cells showed a defect in GRα binding to DEX resulting in diminished translocation to the nucleus, GRα localization was visualized by immunocytochemistry in in vitro-polarized Th17 cell subsets (Fig. 6A). Fluorescent staining showed that the GRα is primarily cytoplasmic before treatment with DEX, and DEX treatment resulted in a significant increase in nuclear GRα in both cell types. This observation was confirmed by Western blot, which showed a decrease in cytoplasmic GRα content (Fig. 6B). Fluorescent microscopy analysis showed a significant increase in nuclear GRα in both Th17 cells 30 min after DEX treatment (Fig. 6C). These results indicate that Th17 cells do express GRα and are not deficient in their ability to translocate GRα to the nucleus upon glucocorticoid treatment.

Although the ability of GRα to bind glucocorticoids and translocate to the nucleus is intact, the defect may lie at the level of DNA binding. Suppression of IL-5 by glucocorticoids involves repression of GATA-3 signaling mediated by GRα binding to the IL-5 NFAT/AP-1-response element and subsequent recruitment of histone deacetylase (22). Studies have shown that IL-17 expression in mouse and human CD4+ T cells is dependent on the NFAT and MAPK pathways (23, 24). Activated GRα may be unable to repress NFAT binding to the IL-17 locus, which would explain the fact that IL-17 production is not attenuated by DEX. Although there are several mechanisms by which Th17 cells might prevent activated GRα from repressing NFAT activity, up-regulation of NFAT expression in response to DEX is one way by which the cell could mask the drug’s effects. To test this hypothesis, polarized

**FIGURE 6.** Mechanism of Th17 cell resistance to DEX treatment. Th17 cells are not deficient in their ability to translocate GRα. A, GR staining by immunofluorescent microscopy in DEX-treated (1 μM) and nontreated Th17 cells. B, Cytoplasmic protein fractions of DEX-treated and nontreated Th17 cells were immunoblotted for GRα and β-actin. Samples were loaded in the following order: Th2_PBS, Th2_DEX, Th17_PBS, and Th17_DEX. C, Fluorescent intensity of nuclear GRα staining in Th17 cells with and without DEX treatment. Data are graphed as mean ± SEM; *, p < 0.05 for DEX compared with nontreated conditions. D and E, Th17 cells were transfected with NFAT-luciferase before stimulation with anti-CD3 and anti-CD28 microbeads (6 h) with or without pretreatment (2 h before beads) with DEX; *, p < 0.05 control (CNTRL) vs CD3/CD28; #, p < 0.05 CD3/CD28 vs CD3/CD28 + DEX.

**TABLE 1.** Summary of experiments examining the effect of DEX on Th17 cell responses.

<table>
<thead>
<tr>
<th>Condition</th>
<th>IL-17</th>
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**Notes:** 
- + indicates increase,
- # indicates decrease,
- AHR increase in response to methacholine challenge.
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T<sub>H</sub>2 and T<sub>H</sub>17 cells were transfected with a NFAT luciferase reporter plasmid and were stimulated with anti-CD3 and anti-CD28 microbeads in the presence or absence of DEX (Fig. 6, C and D). DEX significantly inhibited NFAT luciferase activity in T<sub>H</sub>17 cells, discounting the concept that NFAT activity is steroid independent in T<sub>H</sub>17 cells.

**Discussion**

We have shown that reconstitution of SCID mice with T<sub>H</sub>2 or T<sub>H</sub>17 cells in a model of Ag-induced airway inflammation lead to differential chemokine profiles and cellular influx to the airways. Adoptive transfer of T<sub>H</sub>17 cells resulted in increased levels of CXC chemokines and G-CSF in the BAL fluid and LH following Ag provocation. We do not believe this is due to homeostatic proliferation due to the short time frame of the transfer model (25) as well as similar findings were observed in WT mice (Fig. 4). Moreover, the experiment in WT mice vs IL-17RA KO mice demonstrated that IL-17RA signaling is required for the induction of KC and G-CSF, as well as neutrophil recruitment after T<sub>H</sub>17 T cell transfer (Fig. 4). This was associated with neutrophil influx to the airways and is exacerbated by DEX treatment. Animal-transferred T<sub>H</sub>2 cells in this model exhibit a typical T<sub>H</sub>2 phenotype characterized by the influx of lymphocytes and eosinophils to the airways and are sensitive to DEX treatment. The chemokine and inflammatory responses elicited by T<sub>H</sub>17 cell transfer primarily involves signaling through the IL-17R. This is consistent with the recent study by Liang et al. (26) that showed that IL-22, another product of T<sub>H</sub>17 cells, played a limited role in neutrophil recruitment in an adoptive transfer model compared with IL-17A or IL-17A/F heterodimer. Despite differential chemokine and cellular responses, both T<sub>H</sub>2 and T<sub>H</sub>17 recipient animals exhibited increased AHR and mucus secretion. T<sub>H</sub>17 cells secrete IL-17A and F, IL-6, IL-22, and TNF-α (5). Transfer of T<sub>H</sub>17 cells to IL-17R KO mice showed a substantial decrease in CXC chemokine expression, G-CSF, IL-6 and lung neutrophilia confirming that the T<sub>H</sub>17 cells are migrating to the airways to initiate a response and IL-17R signaling is necessary for the phenotype associated with their transfer. However, the individual contributions of IL-17A or IL-17F homodimers and IL-17A/F heterodimers in AHR remains to be determined.

It has been suggested that IL-17 modulates allergic airway inflammation by dampening Th2 cytokine responses (14, 27). One study showed that Ab neutralization of IL-17 before OVA challenge in sensitized mice resulted in decreased neutrophil influx to the airways but increased airway eosinophilia that those authors attributed to enhanced serum and BAL fluid IL-5 levels in these animals (27). We found that the transfer of T<sub>H</sub>17 cells to WT BALB/c mice resulted in very low and variable Th2 cytokine responses and the IL-17R KO mice did not exhibit an exacerbated Th2 response. One explanation of these divergent findings is that IL-17 signaling is required for the initiation of Ag-mediated airway inflammation but functions to dampen Th2 responses thereafter. This was suggested by studies showing that IL-17R KO mice exhibited decreased airway eosinophilia and IL-5 in an OVA-induced model of pulmonary inflammation, while treating WT animals with exogenous IL-17 reduced Th2 cytokine levels in BAL and LH and eosinophil influx (14). The former IL-17R KO data are in agreement with what we have found in our model of T<sub>H</sub>17-induced airway inflammation. To date, the ability of T<sub>H</sub>17 cells to directly regulate Th2 cells has not been shown. However, regulation between Th2 and T<sub>H</sub>17 may not be as important as the possibility that these Th cell populations are mediating distinct endophenotypes of asthma. Asthma can be classified as atopic (allergic) and nonallergic. Patients with nonatopic asthma do not have elevated IgEs, tend to have more airway neutrophilia, and are clinically steroid resistant (12). The data presented in our model system support a role for T<sub>H</sub>17 cells in nonatopic disease.

DEX treatment of T<sub>H</sub>17 cell-reconstituted animals resulted in increased numbers of neutrophils in the airways following allergen challenge. The mechanism of increased neutrophil numbers in DEX-treated animals reconstituted with T<sub>H</sub>17 cells is not clear. The expression of IL-17 and CXCL8 is increased in the sputum of asthmatic patients and positively correlates with each other and with neutrophil levels in the sputum (28). Our data suggest that increased levels of neutrophil chemotactants and G-CSF, which has been shown to be an important survival factor for neutrophils, may be a mechanism of enhanced recruitment and survival of neutrophils following DEX treatment in T<sub>H</sub>17-reconstituted animals. This is fitting with published reports that corticosteroids down-regulate the CC chemokines CCL2 and CCL11 while exacerbating the CXCL8 response in the airways of asthmatic patients (29). This same study found that corticosteroids decreased airway eosinophilia but increased the number of neutrophils in the airways. Neutrophils are relatively steroid resistant compared with T cells and eosinophils and glucocorticoids enhance survival of neutrophils in vitro (10, 30). In vitro neutralization of another neutrophil survival factor GM-CSF did not alter neutrophil survival following glucocorticoid treatment (31). Glucocorticoids exert their effects through binding the GR, resulting in nuclear translocation and transactivation of genes containing glucocorticoid-response elements (32). It has been suggested that human neutrophils express higher levels of the dominant-negative isoform of the GR, GRβ (19), rendering them nonresponsive to glucocorticoids. However, murine cells do not express GRβ and we observed equivalent nuclear translocation of GR to the nucleus of Th2 and T<sub>H</sub>17 cells and a similar ability to inhibit NFAT transcriptional activation.

Multiple mechanisms of steroid-resistant asthma have been described. One study found that steroid-resistant asthmatics fell into two categories based on GR-binding and expression patterns; one group of patients exhibited increased GR number but reduced GR binding affinity for glucocorticoids, whereas another subset of steroid-resistant patients had a GR-binding affinity similar to that of steroid-sensitive patients, but reduced GR expression per cell (33). Future studies will need to examine GRα binding to regions within the Il17 and Il22 loci.

In contrast to the T<sub>H</sub>17 transfer model, in the Th2 transfer model both lymphocyte and eosinophil recruitment to the airways of Th2 recipient animals treated with DEX and AHR was reduced by DEX treatment. The reduction in lymphocytes may be due to differential DEX sensitivity of chemokines necessary for T cell recruitment or proliferation in vivo. We did not observe differences in T cell apoptosis of Th2 or T<sub>H</sub>17 cells in vitro. Both cells showed >85% viability after DEX treatment for 24 h (data not shown). However, this does not exclude a potential role for differential proliferation or apoptosis in vivo. AHR was significantly improved with DEX treatment, but not to the same levels as the effect of DEX on airway inflammation. AHR is a hallmark feature of asthma and can generally be separated into two categories, variable AHR that occurs during an allergen-induced late asthmatic response and persistent AHR. Although some studies link airway inflammation with AHR, it has been suggested that AHR, especially persistent AHR, can occur in the absence of airway inflammation (34). Tourouy et al. (35) showed AHR occurred independent of eosinophil influx to the airways in a model of house dust mite-mediated airway inflammation. Clinically, administration of a mAb to IL-5 to asthmatic patients also significantly decreased the number or eosinophils in the sputum without altering AHR. In our model system, AHR is mediated by the CD4<sup>+</sup> cell populations
transferred to the mouse in a mast cell/IgE-independent manner. Mast cells are resident in vascularized tissue and express high levels of the IgE receptor FcεRI. IgE binding and Ag cross-linking activates mast cells to release inflammatory mediators including histamine, leukotrienes, cytokines, and chemokines, resulting in bronchoconstriction (37). Mast cells can potentiate Th2-mediated allergic inflammation through the release of IL-5 that is important in eosinophil survival and the release of histamine that directs dendritic cells to secrete IL-4 polarizing naïve cells toward a Th2 phenotype (38, 39). Mast cells are sensitive to glucocorticoids; therefore, it is possible that a mast cell-dependent model system would show that Th2-induced AHR is more responsive to DEX treatment.

We have shown that reconstitution of SCID mice with T\(_{H2}\) cells in the setting of Ag provocation induces CXC chemokine and G-CSF secretion and neutrophil influx to the airways and is sufficient to induce mucus hyperplasia and AHR. In the setting of T\(_{H17}\) cell transfer, chemokine secretion, cellular influx to the airways, and AHR were not sensitive to DEX treatment in these studies. Conversely, in the setting of Th2 cell transfer, cytokine secretion, eosinophil influx to the airways, and AHR were sensitive to DEX. These data highlight the complex relationships between airway inflammation and AHR and support the concept that T\(_{H17}\) cells may be critical mediators of steroid-resistant airways inflammation and AHR.

Disclosures
The authors have no financial conflict of interest.

References