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GPR17 Regulates Immune Pulmonary Inflammation Induced by House Dust Mites

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Antagonists of the type 1 cysteinyl leukotriene receptor (CysLT1R) are efficacious for bronchoconstriction in humans with bronchial asthma; however, the clinical response to these drugs is heterogeneous. In particular, how CysLT1R expression and function are constitutively regulated in vivo is not known. In this study, we show that a seven-transmembrane receptor, GPR17, negatively regulates the CysLT1R-mediated inflammatory cell accumulation in the bronchoalveolar lavage fluid and lung, the levels of IgE and specific IgG1 in serum, and Th2/Th17 cytokine expression in the lung after intranasal sensitization and challenge with the house dust mite (extract of *Dermatophagoides farinae* (*Df*)) in mice. Sensitization of naive wild-type recipients with *Df*-pulsed bone marrow-derived dendritic cells of each genotype or sensitization of each genotype with *Df*-pulsed wild-type bone marrow-derived dendritic cells and *Df* challenge revealed markedly increased pulmonary inflammatory and serum IgE responses for GPR17-deficient mice as compared with wild-type mice and reduced responses in the genotypes lacking CysLT1R. These findings reveal a constitutive negative regulation of CysLT1R functions by GPR17 in both the Ag presentation and downstream phases of allergic pulmonary inflammation. *The Journal of Immunology*, 2010, 185: 1846–1854.

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The online version of this article contains supplemental material.

Abbreviations used in this paper: b, bronchi; BAL, bronchoalveolar lavage; BMDC, bone marrow-derived dendritic cell; cys-LT, cysteinyl leukotriene; CysLT1R, type 1 cysteinyl leukotriene receptor; DC, dendritic cell; *Df*, extract of *Dermatophagoides farinae*; Eos, eosinophils; LNs, lymph node; LT, leukotriene; Lym, lymphocytes; MΦ, macrophage; PSM, polymorphonuclear neutrophil; SMA, α-smooth muscle actin; v, vessels; WT, wild-type.

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(LN), inflammatory cell infiltration in the bronchoalveolar lavage (BAL) fluid and the bronchovascular bundles of lung tissue, marked increases in total IgE and Df-specific IgG1, and Th2/Th17 cytokine expression in the lung. In wild-type (WT) mice, these responses are modest but are dependent on CysLT1R. These findings reveal the role of CysLT1R in WT C57BL6 mice and emphasize the separate negative regulatory effects of GPR17 on CysLT1R functions in DCs and in the downstream cellular and humoral responses of allergic pulmonary inflammation.

Materials and Methods

Mice

Cysltr1−/− mice were originally generated from embryonic stem cells from C57BL6 mice (12) and were maintained by breeding with C57BL6 mice; 15 generations (N15) were used. Gpr17−/− mice (Delta-gen, San Mateo, CA) were established from 129-derived embryonic stem cells, were backcrossed onto the C57BL6 background for seven to eight generations, and N7 and N8 generations were used (23). To generate GPR17/CysLT1R double-deficient (Gpr17/Cysltr1−/−) mice, Gpr17−/− males and Cysltr1−/− females were bred to obtain Gpr17−/−/Cysltr1−/− females. The Gpr17−/−/Cysltr1−/− males and Gpr17−/−/Cysltr1−/− females were further bred to obtain Gpr17−/−/Cysltr1−/−/Cysltr1−/− males and Gpr17−/−/Cysltr1−/−/Cysltr1−/− females. The Gpr17−/−/Cysltr1−/−/Cysltr1−/− mice were viable and had no apparent abnormalities up to at least 12 mo of age. WT littermates from breeding for Cysltr1−/−, Gpr17−/−, and Gpr17−/−/Cysltr1−/− strains were used. Eight- to 10-wk-old male and female mice were used. All animal studies were approved by the Animal Care and Use Committee of the Dana-Farber Cancer Institute.

Active sensitization and challenge with repeated intranasal injections of Df

Mice received 1 μg Df (Greer Laboratories, Lenoir, NC) intranasally twice per week for 3 wk as described (27). Two days after the last injection, mice were killed by i.p. injection of pentobarbital.

BAL fluid cell analysis

Two days after the last intranasal injection, the trachea was cannulated and BAL fluid was obtained by three repeated lavages with 0.75 ml Ca2+- and Mg2+-free PBS with 1 mM EDTA. The BAL fluid was centrifuged at 500 × g for 5 min. Cells were resuspended in 0.2 ml PBS with 1% BSA, and the total cells were counted manually with a hemocytometer. For the differential cell counts of macrophages, neutrophils, eosinophils, and lymphocytes, the cells were cytospun onto a glass slide and stained with Diff-Quik (Dade Behring, Newark, DE), and cell types in a total of 200 cells were identified by morphologic criteria.

Histology

The lung tissues were excised, and the left lung was fixed and stained as described previously (16). For general morphology, tissue sections were stained with H&E. The extent of cellular infiltration in the bronchovascular bundles was assessed in a blinded manner. Congo red staining was used to identify eosinophils, and periodic acid-Schiff staining was used to assess mucus and goblet cells. To assess vascular smooth muscle hyperplasia, some tissue sections were stained with mouse anti-α-smooth muscle actin mAb (clone 1A4; Covance, Princeton, NJ) and with the LSAB+ system (Dako, Carpinteria, CA) according to the manufacturers’ instructions. The total smooth muscle cell numbers and the thickness of arteriolar medial muscular layer (tunica media) were quantified by ImageJ (National Institutes of Health, Bethesda, MD) on smooth muscle actin-stained sections as previously described (27). Briefly, digital images of five medium-sized muscular layer (tunica media) were quantified by ImageJ (National Institutes of Health, Bethesda, MD) on smooth muscle actin-stained sections as previously described (27). Briefly, digital images of five medium-sized arteries with a diameter of 30–50 μm were taken from each slide, and the endothelium and smooth muscle cell per 100-μm basement membrane and the mean thickness of the medial arteriolar walls in five arterioles from three to five mice per group.

For immunohistochemistry to detect CysLT1R, mouse lung tissues were embedded in Tissue-Tek OCT compound (Sakura Finetek, Torrance, CA) and cut into 5-μm-thick sections. Frozen sections were fixed with 4% paraformaldehyde, washed, and incubated with polyclonal rabbit anti-CysLT1R IgG (RB34, against the conserved sequence DDKNTEC-FFEPQNN of extracellular loop 3 of both mouse and human CysLT1R, 30 μg/ml) (23). Immunoreactivities were visualized with a rabbit ABC peroxidase staining system (Santa Cruz Biotechnology, Santa Cruz, CA) according to the manufacturer’s instructions. The slides were analyzed with a Leica DM LB2 microscope (Leica Microsystems, Wetzlar, Germany). The images were taken with a Nikon digital camera DXM 1200 with Nikon ACT-1 (version 2.70) image acquisition software.

Measurement of total IgE and Df-specific IgG1

Sera were collected by cardiac puncture 2 d after the last intranasal injection. Total IgE was determined with an ELISA kit (BD Biosciences, San Jose, CA). Df-specific IgG1 was measured as described (28). Briefly, 96-well plates were coated with a 5 μg/ml solution of Df and incubated with diluted serum followed by alkaline phosphatase-conjugated anti-mouse IgG1 (SouthernBiotech, Birmingham, AL) and p-nitrophenyl phosphate substrate (Sigma-Aldrich, St. Louis, MO).

Measurement of cytokine mRNA expression in the lung

Total RNA was isolated from the right lungs with TRizol reagent (Invi- trogen, Carlsbad, CA) according to the manufacturer’s protocol. Quantities of mRNA for IL-4, IL-5, IL-13, IL-17A, and IFN-γ were measured relative to GAPDH using the Mx3000P real-time PCR system (Agilent Technologies, Santa Clara, CA) with gene-specific primers.

Flow cytometry

Macrophages were harvested by peritoneal lavage with ice-cold PBS, washed, and incubated in RPMI 1640 medium containing 10% FBS for 3 h at 37°C in a humidified atmosphere with 5% CO2. Adherent cells were detached with 4 mg/ml lidocaine and 5 mM EDTA in PBS and were incubated with polyclonal rabbit anti-CysLT1R IgG (RB34, 5 μg/ml) and allophycocyanin-conjugated donkey anti-rabbit IgG. Nonspecific rabbit IgG (Jackson ImmunoResearch Laboratories, West Grove, PA) was used as a control. Analyses were performed on a FACSCan flow cytometer (BD Biosciences), and data were analyzed with the FlowJo software (Tree Star, Ashland, OR).

Cytokine production by parabronchial LN cells after ex vivo restimulation with Df

Two days after the last intranasal injection, three parabronchial LNcs were excised from each mouse and homogenized. The cell suspensions were filtered through a 70-μm cell strainer, centrifuged at 300 × g for 5 min at room temperature, and resuspended in RPMI 1640 medium containing heat-inactivated 10% FBS. After the total number of cells was counted for each mouse, cells were cultured at 2 × 106 cells/ml (100 μl) in the presence of 20 μg/ml Df in a 96-well plate for 72 h. The concentrations of IL-4, IL-5, IL-17A, and IFN-γ in the supernatants were measured with ELISA kits (eBioscience, San Diego, CA).

Transfer of Df-pulsed BMDCs into mice and Df challenge

Adoptive transfer of Df-pulsed BMDCs into naive mice was carried out as described (29) with modifications. Bone marrow cells were harvested from femurs and tibiae of each mouse and cultured in RPMI 1640 medium supplemented with 10% heat-inactivated FBS, 100 U/ml penicillin, 100 μg/ml streptomycin, 2 mM L-glutamine, 50 μM 2-ME, and recombinant mouse GM-CSF as described (30). Floating cells were harvested on day 8 and pulsed with either PBS or 100 μg/ml Df at a concentration of 1 × 106 cells/ml in a 35-mm culture dish (Sumilon Celltight X; Sumitomo Bakelite, Tokyo, Japan) for 24 h. The next day, the cells were washed twice with PBS and resuspended in PBS. Cells (1 × 105) in 50 μl were transferred intranasally to recipients that were briefly anesthetized with isoflurane. At days 10 and 14 after DC transfer, recipients were briefly anesthetized with isoflurane and pulsed with either PBS or 100 μg/ml Df. At a concentration of 1 × 106 cells/ml in the supernatants were measured with ELISA kits (eBioscience, San Diego, CA).
respective roles of CysLT,R and GPR17. Mice received intranasal injections of 1 μg of Df or PBS twice per week for 3 wk and were killed 48 h after the last injection (27). Df-challenged WT mice had an increased cellular infiltration in BAL fluid composed of monocytes/macrophages, neutrophils, eosinophils, and lymphocytes as compared with PBS-injected WT mice. Df-challenged Cysltr1<sup>−/−</sup> mice showed no increase in any of these cell types in BAL fluid as compared with Df-challenged WT mice. In contrast, Df-challenged Gpr17<sup>−/−</sup> mice had significant and marked increases in BAL fluid cell numbers of neutrophils, eosinophils, and lymphocytes as compared with Df-challenged WT mice. This exaggerated cellular influx into the BAL fluid of Gpr17<sup>−/−</sup> mice was completely abrogated in Df-challenged Gpr17/Cysltr1<sup>−/−</sup> mice (Fig. 1A).

Histologic analysis of the bronchovascular bundles in the lung reflected the cellular influx in the BAL fluid. There was a modest increase in cellular infiltration in WT mice that was largely absent in Cysltr1<sup>−/−</sup> mice, and there was a marked increase in the cellular infiltration in Gpr17<sup>−/−</sup> mice that was abolished in the Gpr17/Cysltr1<sup>−/−</sup> mice (Fig. 1B, H&E). Congo red staining showed that the cellular infiltration in WT and especially in Gpr17<sup>−/−</sup> mice was enriched with eosinophils as compared with the infiltration in the absence of CysLT,R (Supplemental Fig. 1A, CR). Goblet cell metaplasia with mucus hyperproduction was particularly prominent in Df-challenged Gpr17<sup>−/−</sup> mice compared with similarly challenged WT mice as assessed by periodic acid-Schiff staining and was abolished in the Cysltr1<sup>−/−</sup> and Gpr17/Cysltr1<sup>−/−</sup> mice (Supplemental Fig. 1A, PAS). Unexpectedly, Df-challenged Gpr17<sup>−/−</sup> mice had strikingly increased smooth muscle cells in the vasculature as assessed by immunohistochemical staining for α-smooth muscle actin (Fig. 1B, SMA). The numbers of α-smooth muscle actin-positive cells as well as thickness of the α-smooth muscle actin-staining layer were significantly increased in Df-challenged Gpr17<sup>−/−</sup> mice as compared with Df-challenged WT mice (Supplemental Fig. 1B).

After sensitization and challenge with Df, Cysltr1<sup>−/−</sup> mice had significantly less total serum IgE and Df-specific IgG1 as compared with similarly treated WT mice (Fig. 2). In contrast, Df-challenged Gpr17<sup>−/−</sup> mice had significantly increased levels of total IgE and Df-specific IgG1 as compared with WT controls, and these increases were completely abrogated in Df-challenged Gpr17/Cysltr1<sup>−/−</sup> mice. PBS-injected Gpr17<sup>−/−</sup> mice also had a significantly increased total IgE level at baseline as compared with WT controls. The levels of Df-specific IgG2a in all serum samples were below the detection limit of the ELISA.

To assess the Th2/Th17/Th1 cell cytokine expression in the lungs after sensitization and challenge with Df, total RNA was isolated from the right lungs of WT, Cysltr1<sup>−/−</sup>, Gpr17<sup>−/−</sup>, and Gpr17/Cysltr1<sup>−/−</sup> mice.

**FIGURE 1.** GPR17 deficiency increases CysLT,R-mediated Df-induced pulmonary inflammation. A, Inflammatory cell counts in BAL fluid. For active sensitization and challenge, mice received 1 μg of Df (filled columns) or PBS (open columns) by intranasal injection twice per week for 3 wk, and BAL was performed 2 d after the last injection. Total and differential cell counts for monocytes/macrophages, neutrophils, eosinophils, and lymphocytes are shown. Values are the means ± SEM (n = 8–10) combined from three independent experiments. *p < 0.01; **p < 0.05. B, Histologic analyses of the lung. After BAL, lung tissues were fixed with paraformaldehyde and stained with H&E. Immunohistochemistry was performed with mouse mAb to α-smooth muscle actin and ABC-alkaline phosphatase reagent, visualized in red. Scale bars, 100 μm for H&E (original magnification ×200); 50 μm for SMA (original magnification ×400). b, bronchi; MΦs, macrophages; SMA, α-smooth muscle actin; v, vessels.
Cysltr1$^{-/-}$ mice, and quantitative RT-PCR was performed. In WT mice, sensitization and challenge with Df significantly increased the expression of mRNAs for IL-4, IL-5, and IL-13, but not of mRNAs for IL-17A or IFN-$\gamma$, as compared with PBS-injected controls (Fig. 3). Df-challenged Gpr17$^{-/-}$ mice had no increase in mRNA expression of IL-4, IL-5, IL-13, IL-17A, and IFN-$\gamma$ as compared with PBS-injected controls. Df-challenged Gpr17/Cysltr1$^{-/-}$ mice had a significant further increase in expression of IL-4, IL-5, and IL-13, along with a significant increase in IL-17A expression and a decrement in IFN-$\gamma$ expression, as compared with Df-challenged WT mice; each of these changes was completely abrogated in Df-challenged Gpr17/Cysltr1$^{-/-}$ mice (Fig. 3). The aggregate findings for pulmonary inflammation, for levels of serum total IgE and Df-specific IgG1, and for cytokine expression in lungs with Df sensitization and challenge reveal a core role of CysLT1R in an integrated Th2 type response of WT mice that is markedly exaggerated and includes IL-17A in the absence of regulation by GPR17.

GPR17 deficiency upregulates Df-induced CysLT1R expression in inflammatory cells in lungs

As we had previously observed increased expression of CysLT1R by flow cytometry as well as increased function in in vitro bone marrow-derived macrophages subjected to GPR17 knockdown (23), we used flow cytometry to identify CysLT1R expression on...
resting peritoneal macrophages. There was significant CysLT1R expression in the macrophages from WT mice but no expression in the cells from Cysltr1<sup>−/−</sup>, Gpr17<sup>−/−</sup>, and Gpr17/Cysltr<sub>1</sub><sup>−/−</sup> mice (Supplemental Fig. 2A), thereby showing the specificity of the Ab. There was further increased CysLT1R expression in the macrophages from Gpr<sub>17</sub><sup>−/−</sup> mice as compared with those from WT mice (Supplemental Fig. 2B). We next performed immunohistochemical staining for CysLT1R in the lungs from PBS-injected or Df-sensitized and challenged WT, Cysltr1<sup>−/−</sup>, Gpr17<sup>−/−</sup>, and Gpr17/Cysltr<sub>1</sub><sup>−/−</sup> mice. Many macrophages and polymorphonuclear neutrophils (PMNs), but not eosinophils or lymphocytes, in the lung tissue of Df-challenged WT mice stained positively for CysLT1R as compared with the lack of staining in lung tissue from PBS-injected WT mice or from Df-challenged Cysltr1<sup>−/−</sup> or Gpr17/Cysltr<sub>1</sub><sup>−/−</sup> mice. Furthermore, there was stronger positive staining for CysLT1R in macrophages and PMNs in Df-challenged Gpr17<sup>−/−</sup> mice (Fig. 4) as well as slight but definite staining in bronchial smooth muscle cells in lung of this genotype (data not shown). The fact that the eosinophils and lymphocytes were not stained in Df-challenged lungs of WT or Gpr17<sup>−/−</sup> mice suggests that their presence is part of an integrated cytokine/chemokine-directed inflammatory response rather than cys-LT-dependent migration. We were not
able to detect CysLT₁R expression on the alveolar walls or vasculature of the bronchovascular bundles of any genotype.

**Sensitization of WT mice with Df-pulsed GPR17-deficient BMDCs enhances pulmonary, LN, and Ig responses upon challenge**

To determine whether the exaggerated inflammatory phenotype in the lungs of Gpr17⁻/⁻ mice involved the Df-presenting function and aferent aspect of the integrated response, we adoptively transferred 1 x 10⁶ Df-pulsed BMDCs from the four genotypes (WT, Cysltr1⁻/⁻, Gpr17⁻/⁻, and Gpr17/Cysltr1⁻/⁻) to WT recipients, challenged them with 1 μg of Df at days 10 and 14, and killed them for assessment at day 16 (29). The numbers of neutrophils and eosinophils in BAL fluid with Df challenge were increased in WT mice sensitized with Df-pulsed WT BMDCs (WT BMDCs→WT mice), whereas these inflammatory cells were absent with Df challenge of WT mice receiving PBS-treated WT BMDCs (data not shown) or Df-pulsed BMDCs from Cysltr1⁻/⁻ mice (Cysltr1⁻/⁻ BMDCs→WT mice) (Fig. 5A). The mere sensitization of WT mice with Df-pulsed BMDCs from Gpr17⁻/⁻ mice slightly increased the numbers of neutrophils and eosinophils in the BAL fluid (data not shown), and these numbers rose 2- to 3-fold with Df challenge in association with lymphocytes (Gpr17⁻/⁻ BMDCs→WT mice) (Fig. 5A). This augmentation of cell recruitment to BAL fluid was lost with sensitization by Df-pulsed BMDCs from Gpr17/Cysltr1⁻/⁻ mice (Gpr17/Cysltr1⁻/⁻ BMDCs→WT mice). These results suggest that GPR17 is a negative regulator for CysLT₁R-dependent, DC-mediated allergic pulmonary inflammation.

We harvested the lungs for histology and the LNs for cell counts and restimulation from these mice after BAL. Histologic analysis of the bronchovascular bundles revealed that the cellular infiltrates were moderate in the Gpr17⁻/⁻ BMDCs→WT mice (data not shown). The LN cells were dissociated, counted, and restimulated at a concentration of 2 x 10⁶ cells/ml with 20 μg/ml Df for 72 h, and the cytokine concentrations in the supernatant were measured with ELISAs. The total number of LN cells was decreased in Cysltr1⁻/⁻ BMDCs→WT mice and significantly increased in Gpr17⁻/⁻ BMDCs→WT mice as compared with WT BMDCs→WT mice (Fig. 5B). The total numbers of LN cells from Gpr17/Cysltr1⁻/⁻ BMDCs→WT mice were minimal and comparable to the numbers for Cysltr1⁻/⁻ BMDCs→WT mice (Fig. 5B). Df restimulation of LN cells from WT mice that received PBS-treated BMDCs from any genotype of donor mice did not yield any detectable cytokines (data not shown). LN cells of WT BMDCs→WT mice responded to ex vivo restimulation with Df with increased levels of IL-17A and IFN-γ, as well as minimal levels of IL-5. IL-5 was selectively increased in ex vivo Df-restimulated LN cells from Gpr17⁻/⁻ BMDCs→WT mice (Supplemental Fig. 3). We did not detect IL-4 production. Of note was the finding that restimulation of LN cells of Cysltr1⁻/⁻ BMDCs→WT mice or Gpr17/Cysltr1⁻/⁻ BMDCs→WT mice failed to produce any detectable cytokines even though the cell numbers for restimulation were equivalent.

We assessed humoral Th2 immune responses in this cohort by measuring total IgE and Df-specific IgG1. As shown in Fig. 5C, Cysltr1⁻/⁻ BMDCs→WT mice had significantly less total IgE and Df-specific IgG1 as compared with WT BMDCs→WT mice. In contrast, Gpr17⁻/⁻ BMDCs→WT mice had slightly increased levels of total IgE and Df-specific IgG1 as compared with WT BMDCs→WT mice, and these increases were significantly reduced in Gpr17/Cysltr1⁻/⁻ BMDCs→WT mice (Fig. 5C). Thus,
the contribution of CysLT1R to the function of Df-pulsed BMDCs in mediating sensitization for effective Df challenge is apparent by the cell number of the draining LNs and the levels of humoral IgE/IgG1 and the cellular influx into the BAL fluid and lung on the efferent side.

Sensitization of GPR17-deficient mice with Df-pulsed WT BMDCs enhances pulmonary, LN, and Ig responses upon challenge

To determine whether the CysLT1R-mediated recipient effector functions are also increased in the absence of GPR17, we sensitized WT, Cysltr1/−/−, Gpr17/−/−, and Gpr17/Cysltr1/−/− mice with Df-pulsed BMDCs from WT mice, challenged them with Df, and assessed for pulmonary and associated LN and Ig responses. As compared with WT recipients, the numbers of neutrophils and eosinophils in BAL fluid were significantly decreased in Cysltr1/−/− recipients (Fig. 6A). In contrast, the numbers of neutrophils and eosinophils along with lymphocytes were significantly increased in Gpr17/−/− recipients as compared with WT recipients, and this response was abolished in Gpr17/Cysltr1/−/− recipients. Histologic analysis of the bronchovascular bundles revealed that the cellular infiltrates were minimal in WT recipients, absent in Cysltr1/−/− and Gpr17/Cysltr1/−/− mice, and significantly increased in Gpr17/−/− mice (data not shown).

Moreover, as compared with WT recipients, the total number of LN cells from Cysltr1/−/− recipients was significantly decreased, and that from Gpr17/−/− recipients was strikingly increased. This increased LN cell number was absent in Gpr17/Cysltr1/−/− recipients (Fig. 6B). The restimulated LN cells from WT recipients generated IL-5, IL-17A, and IFN-γ, and the amounts of these cytokines were 4- to 10-fold higher per cell in Gpr17/−/− recipients. There was no generation of cytokines with Df restimulation of LN cells from Cysltr1/−/− and Gpr17/Cysltr1/−/− recipients, again on a per cell basis (Supplemental Fig. 4).

As shown in Fig. 6C, Cysltr1/−/− recipients had significantly less total IgE and Df-specific IgG1 as compared with WT recipients. In contrast, Gpr17/−/− recipients had ∼2-fold and 1.5-fold increases in total IgE and Df-specific IgG1, respectively, as compared with WT recipients, and these increases were significantly reduced in Gpr17/Cysltr1/−/− recipients (Fig. 6C). Thus, these results reveal additional GPR17-regulated CysLT1R functions that are downstream of the DC Ag presentation phase but yet also influence the inflammatory response in lungs, the draining LNs, and Th2-regulated Igs.

GPR17-deficient mice sensitized with Df-pulsed GPR17-deficient BMDCs

Finally, we adoptively transferred Df-pulsed Gpr17/−/− or Gpr17/Cysltr1/−/− BMDCs into Gpr17/−/− recipients to determine whether DC CysLT1R functions can be apparent in Gpr17/−/− recipients. The BAL fluid in Gpr17/−/− BMDCs→Gpr17/−/− mice was enriched for eosinophils, neutrophils, and lymphocytes, and this augmented response of Gpr17/−/− recipients was abrogated in Gpr17/Cysltr1/−/− BMDCs→Gpr17/−/− mice (Fig. 7A). Histologic analysis revealed that the cellular infiltrates were markedly increased in Gpr17/−/− BMDCs→Gpr17/−/− mice, and the increase was reduced in Gpr17/Cysltr1/−/− BMDCs→Gpr17/−/− mice (Fig. 7B). The levels of IL-5, IL-17A, and IFN-γ with restimulation of LN cells (Supplemental Fig. 5B) and of total IgE and Df-specific IgG1 in serum in Gpr17/−/− BMDCs→Gpr17/−/− mice were also reduced in Gpr17/Cysltr1/−/− BMDCs→Gpr17/−/− mice (Fig. 7C). On

FIGURE 7. GPR17-deficient mice sensitized with Df-pulsed GPR17-deficient BMDCs. A, Inflammatory cell count in BAL fluid. BMDCs from Gpr17/−/− and Gpr17/Cysltr1/−/− mice were pulsed with Df at 100 μg/ml for 24 h, and 10⁶ cells were administered intranasally for sensitization of Gpr17/−/− recipients. Recipients were challenged with 1 μg of Df intranasally at days 10 and 14 and killed at day 16 for analysis. Total and differential cell counts for BAL fluid monocytes/macrophages, neutrophils, eosinophils, and lymphocytes are shown. B, Parabronchial LN cell numbers. Parabronchial LN cells were harvested and counted, and total cell numbers are shown. C, Levels of total IgE and Df-specific IgG1 in serum. Total IgE and Df-specific IgG1 in sera of Df-challenged mice were measured by ELISA. Values are the means ± SEM (n = 10) combined from two independent experiments. *p < 0.01. MΦs, macrophages.
inspection, the magnitude of the cellular infiltrate in the BAL fluid, the cell numbers in the draining LNs, and the levels of serum IgE/IgG1 were comparable to the findings for Df-pulsed WT BMDCs adoptively transferred into Gpr17<sup>−/−</sup> recipients (Fig. 6) and greater than those for Gpr17<sup>−/−</sup> BMDCs adoptively transferred into WT recipients (Fig. 5).

**Discussion**

We find that the absence of GPR17 allows a constitutive increased expression of CysLT<sub>1</sub>R that is further markedly upregulated with an inflammatory response that follows sensitization and challenge with Df. With sensitization and challenge, the phenotype of WT mice includes local cellular infiltration of the lung and BAL fluid, a systemic further increase in total IgE with appearance of Df-specific IgG1, and increased Th2 cytokine transcripts in the lung. In the Gpr17<sup>−/−</sup> mice, there is a further significant increase in cellular infiltration of lung, in total IgE and Df-specific IgG1 in serum, and in Th2 cell cytokine transcripts, along with an increase in transcript for IL-17A and a decrement of transcript for IFN-γ. The concomitant increased expression of CysLT<sub>1</sub>R is evident in the infiltrating pulmonary macrophages and neutrophils in WT mice and is exaggerated in the lungs of Gpr17<sup>−/−</sup> mice. The remarkable distributions of CysLT<sub>1</sub>R effects to both the Df presentation step and the downstream cellular responses were recognized when the four genotypes of mice were sensitized by Df-pulsed BMDCs and Df challenged. When the Df-pulsed BMDCs lacked GPR17, the response of WT recipients was marked but abolished when CysLT<sub>1</sub>R was also absent. Similarly, when the Df-pulsed BMDCs were WT, the local and systemic responses of GPR17-deficient recipients were again marked but abolished when CysLT<sub>1</sub>R was also absent. When the GPR17-regulated, CysLT<sub>1</sub>R-mediated functions were reintegrated by sensitizing Gpr17<sup>−/−</sup> mice with Df-pulsed Gpr17<sup>+/+</sup> BMDCs and challenging them with Df, the magnitude of responses resembled that of WT BMDCs→Gpr17<sup>−/−</sup> mice. These findings reveal that the downstream regulatory functions of GPR17 are profound but under the control of the gate-opening sensitization function of CysLT<sub>1</sub>R on DCs.

A systemic phenotype in naive mice lacking GPR17 is observed as a significant increase in total serum IgE, reminiscent of our previous observation that total serum IgE was reduced in naive BALB/c mice lacking LTC<sub>4</sub> synthase, the critical enzyme for cys-LT biosynthesis (16). An in vitro study has shown that stimulation of IL-4 and CD40-activated human B cells with LTD<sub>4</sub> induces mature epsilon transcripts and increases IgE production (31). Thus, in the absence of GPR17, cys-LTs/CysLT<sub>1</sub>R might promote the generation of IgE-secreting B cells in vivo.

There was slightly increased expression of CysLT<sub>1</sub>R in bronchial smooth muscle cells of Df-challenged Gpr17<sup>−/−</sup> mice but not WT mice. Increased expression of CysLT<sub>1</sub>R in bronchial smooth muscle cells had been noted with OVA-induced chronic pulmonary inflammation with remodeling in the BALB/c strain (17). Previous reports on molecular characterization of the human CysLT<sub>1</sub>R showed that the CysLT<sub>1</sub>R transcripts and proteins are expressed in human lung smooth muscle cells and lung macrophages as assessed by in situ hybridization (5) and by immunohistochemistry (18), respectively. The same group further identified the expression of CysLT<sub>1</sub>R transcripts and proteins in monocytes/macrophages, eosinophils, and a subset of neutrophils in nasal lavage fluid from patients with seasonal allergic rhinitis (19).

We were surprised to observe that Df restimulation of lung-draining LN cells from mice presenting an induced Th2-like pulmonary and systemic response revealed an unselective cytokine response that was, however, entirely CysLT<sub>1</sub>R-dependent. In a pharmacologic study in BALB/c mice sensitized by adoptive transfer of Df-pulsed BMDCs and challenged with Df, the recruitment of eosinophils and the levels of IL-5 in BAL fluid were increased by costimulation with LTD<sub>4</sub> and suppressed by the presence of a CysLT<sub>1</sub>R antagonist (29). Another pharmacologic study showed that the treatment of BALB/c mice with a CysLT<sub>1</sub>R antagonist during OVA sensitization reduced the production of IL-4, IL-5, and IFN-γ in BAL fluid after OVA challenge without affecting the levels of OVA-specific IgE and IgG in serum (32). Whereas these pharmacologic studies suggest that CysLT<sub>1</sub>R activation may augment DC function in both Th2- and Th1-biased immune responses, our findings reveal a role in Th2 and Th17 immune responses in the absence of GPR17. CysLT<sub>1</sub>R can be upregulated after TCR activation on mouse T cells in vitro and mediates LTD<sub>4</sub>-elicited calcium flux and migration toward LTD<sub>4</sub> (33). An Affymetrix GeneChip analysis with various human T cell subsets has revealed that CysLT<sub>1</sub>R expression is upregulated in Th2 and effector memory T cells as compared with Th1 and central memory T cells (34). Thus, our future studies may find that Th2 cells as well as Th17 cells preferentially migrate from the regional LNs to lung after Df challenge in Gpr17<sup>−/−</sup> mice.

Another surprising finding was the appearance of smooth muscle cell hyperplasia in the pulmonary vasculature of the Gpr17<sup>−/−</sup> mice. The abolition of this finding in the Gpr17/Cysltr1<sup>−/−</sup> mice indicates a critical mitogenic role for CysLT<sub>1</sub>R in vascular smooth muscle cells when GPR17 dampening is lacking. Vascular remodeling is one of the key features in allergen-induced pulmonary inflammation in mice, such as intense inhalation challenge with OVA (35) or Df (36). In vitro studies have shown that LTD<sub>4</sub> can potentiate epidermal growth factor-driven human airway smooth muscle cell proliferation (37) and that LTD<sub>4</sub> can promote TGF-β- or IL-13-primed human airway smooth muscle cell proliferation in a CysLT<sub>1</sub>R-dependent manner (38). Recently, Lundquist et al. reported in a similar Df active sensitization and challenge protocol that mice lacking microsomal PGE synthase-1 show an enhanced vascular smooth muscle hyperplasia (27). Thus, both the antiproliferative function of PGE<sub>2</sub> and the GPR17 down-regulation of CysLT<sub>1</sub>R can mitigate the action of mitogenic factors for smooth muscle cells in allergic pulmonary inflammation.

Our findings that C57BL/6 Cysltr1<sup>−/−</sup> and Gpr17/Cysltr1<sup>−/−</sup> mice were protected from pulmonary inflammation both in active Df sensitization and challenge and in Df-pulsed BMDC transfer models with challenge reveal a broad and dose-related role for CysLT<sub>1</sub>R in Ag presentation and downstream responses. Th2-like pulmonary and systemic responses mediated by CysLT<sub>1</sub>R are profoundly downregulated by GPR17 expression. It is conceivable that the homologous human GPR17 may contribute to the heterogeneous responses to CysLT<sub>1</sub>R antagonists in patients with bronchial asthma due to variation in GPR17 regulation of the CysLT<sub>1</sub>R at particular or multiple cell sites.

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**Disclosures**

The authors have no financial conflicts of interest.

**References**


Corrections


The columns were incorrectly identified in the legend for Fig. 2. The second sentence of the legend to Fig. 2 should read as follows: “Total IgE and *Df*-specific IgG1 in serum of PBS-injected (open columns) or *Df*-challenged (filled columns) mice depicted in Fig. 1 are shown.” The results and conclusions of the article remain unchanged.

The online version of this article has been corrected and now differs from the print version as originally published.

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