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A Critical Role for C5L2 in the Pathogenesis of Experimental Allergic Asthma

Xun Zhang,1 Inken Schmudde,1 Yves Laumonnier,1 Manoj. K. Pandey,*, Jennifer R. Clark,‡ Peter König,§ Norma P. Gerard,† Craig Gerard,§ Marsha Wills-Karp,§ and Jörg Köhl*,†


Allergic asthma is a common chronic inflammatory disease with a high prevalence in western countries. It develops as a severe lung disease in response to exposure to inhaled allergens, air pollutants, chemicals, and diverse environmental factors. The clinical manifestations of asthma include wheezing, breathlessness, chest tightness, and coughing. The pathophysiology includes bronchoconstriction, airway hyperresponsiveness (AHR), mucus hyperplasia, elevated IgE production, and pulmonary infiltration of leukocytes such as eosinophils, lymphocytes, and mast cells. Intensive investigations have been focusing on the immunologic basis of asthma. It is now generally believed that asthma arises as a result of dysregulated immune responses in which CD4+ Th2 cells play a central role in disease pathogenesis and pathology (1).

The complement system is an important arm of innate immunity. Besides its well-known function as a lytic effector system in host defense against pathogens, it has recently been shown to regulate adaptive immunity both under steady state conditions and in an inflammatory environment (2). The anaphylatoxins (ATs) C3a and C5a are generated following complement activation and are recognized as proinflammatory mediators of allergic asthma. However, recent studies suggest an unexpected immunoregulatory role for C5a during allergen sensitization (3, 4). C5a exerts its effects mainly through binding to the C5a receptor (C5aR) that is widely expressed (2). C5aR signaling in pulmonary dendritic cells (DCs) has been suggested to regulate DC function and subsequent DC-mediated activation of naïve T cells as a means to control the development of allergen-induced adaptive immune responses (5). In addition to C5aR, the orphan receptor C5aR-like 2 (C5L2) has lately been identified as a second receptor for C5a (6, 7).

C5L2 binds C5a with the same high affinity as C5aR, but has a 20-fold higher affinity for the desarginylated C5a metabolite, C5adesArg, than C5aR (6, 7). C5L2 has also been considered a receptor for other complement fragments including C3a, C3a-desArg, C4a, and C4a-desArg (8, 9), although this still remains controversial as in vitro ligand-binding assays demonstrated no interaction of C5L2 with C3a, C4a, or their metabolites in various cell lines (10).

Binding of C5a to C5aR activates cells through the recruitment of G protein subtypes, including Gx12/13, G13, or G16, resulting in increased intracellular calcium concentration (11), MAPK (7, 12), PI3K (13), and protein kinase B/Akt (14) activation among other pathways (reviewed in Ref. 15). In contrast, C5L2 is uncoupled from G proteins due to the lack of critical intracellular amino acid

Abbreviations used in this paper: AHR, airway hyperresponsiveness; AT, anaphylatoxin; BAL, bronchoalveolar lavage; BM, bone marrow; C5aR, C5a receptor; C5aRKO, C5aR-deficient mice; C5L2, C5a receptor-like 2; C5L2KO, C5L2-deficient mice; DC, dendritic cell; EO, eosinophil; HDM, house dust mite; i.t., intratracheal;Ly, lymphocyte; mDC, myeloid DC; MHC-II, MHC class II; Ne, neutrophil; PAS, periodic acid-Schiff; TMT, total mice; WT, wild-type.
motifs such as DRY and NPXXY (7). This lack of signaling together with its constitutive recycling and the internalization of its ligands suggests that C5L2 may function as a decoy receptor regulating the bioavailability of C5α and thus limiting the C5αR-dependent cell activation (16). In support of this view, C5L2 ligation was found to limit the proinflammatory properties of C5α, providing a negative feedback mechanism to control C5α-mediated inflammatory responses in an in vivo model of immune complex disease (17). Mechanistically, C5L2 was recently shown to negatively modulate C5αR signaling through the β-arrestin pathway (18). In contrast, recent reports have demonstrated signaling functions of C5L2 under physiological and pathological conditions. C5L2 was found to mediate acylation-stimulating protein (C3-desArg)-induced triglyceride synthesis and β-arrestin translocation in transfected HEK293 cells (9). Furthermore, Chen et al. (14) have demonstrated that C5L2 is required for optimal biological activities of C3α and C5α, indicating a positive modulation of C5L2 in C3α- and C5α-mediated cellular responses leading to inflammation. Finally, in a mouse model of moderate sepsis, C5L2-deficient mice (C5L2KOs) exhibited an improved survival rate similar to C5αRKO mice, suggesting that C5L2 exerts proinflammatory effects similar to C5αR signaling (19).

Given the contentious data indicating the involvement of C5L2 in controlling both proinflammatory and anti-inflammatory responses, and the fact that C5α plays critical roles in the development of asthma, we aimed at evaluating the impact of C5L2 in controlling both proinflammatory and anti-inflammatory responses similar to C5αR signaling (19).

AHR was determined by measuring dynamic airway pressure (21) or by forced oscillation technique. Briefly, dynamic airway pressure was determined in anesthetized mice at the indicated time points after the final i.t. injection. Mice were intubated and ventilated at a rate of 120 breaths per minute with a constant tidal volume of air (0.2 ml), and paralyzed with 25 mg/kg weight of decamethonium bromide. After establishment of a stable airway pressure, 25 μg/kg weight of acetylcholine was injected i.v., and dynamic airway pressure measured as airway pressure time index in cm H2O × s−1 was followed for 5 min. Alternatively, airway resistance was measured in anesthetized mice that were mechanically ventilated using a FlexiVent (Scireq, Saint-Urbain, Quebec, Canada). Aerosolized metacholine (50 mg/ml; Sigma-Aldrich) was generated by ultrasonic nebulizer and delivered in-line through the inhalation port for 10 s and airway resistance was measured 2 min later.

Collection of blood and bronchoalveolar lavage cell differentials

Blood was drawn from abdominal aorta and centrifuged. Serum was stored at −80°C for IgE measurements. Bronchoalveolar lavage (BAL) samples were obtained by cannulating the trachea, injecting 1.0 ml ice-cold PBS, and subsequently aspirating the BAL fluid. BAL cells were washed once in PBS and counted using a hemocytometer (Paul Marienfeld, Lauda-Koenigshofen, Germany). Differential cell counts were obtained from BAL cells spun down onto slides and treated with Diff-Quick stain (Dade Behring, Deerfield, IL). A total of 500 cells was morphologically differentiated by light microscopy.

Isolation of pulmonary cells and cytokine measurements

Liberase/DNase I digests of the lungs were prepared to obtain single lung cell suspensions. Single-cell suspensions (2.5 × 106) were restimulated ex vivo with 1 μM OVA for the OVA model, 30 μg/ml HDM for the HDM model, or with medium alone, and incubated at 37°C for 72 h in RPMI 1640 culture medium supplemented with 10% FBS, 2 mM L-glutamine, 100 U/ml penicillin, 100 μg/ml streptomycin (all from Life Technologies Invitrogen, Carlsbad, CA), 1 mM sodium pyruvate (Cellgro Mediatech, Herndon, VA), and 50 μM 2-ME (Sigma-Aldrich). Production of IL-4, IL-5, IL-10, IL-13, IL-17A, and IFN-γ in culture supernatants was determined using DuoSet ELISA kits (R&D Systems, Minneapolis, MN) following the manufacturer’s protocol. The sensitivities were 12 pg/ml for IL-4 and IL-17A; 32 pg/ml for IL-5, IL-10, and IFN-γ; and 62.5 pg/ml for IL-13.

Serum IgE ELISA

To determine total serum IgE levels, microtiter plates (Nunc, Rochester, NY) were coated overnight at 4°C with 50 μl purified rat anti-mouse IgE mAb (BD Pharmingen), followed by biotin-conjugated rat anti-mouse IgE (BD Pharmingen), followed by avidin-peroxidase (Sigma-Aldrich) and one-step ABTS (Pierce) as substrate. Plates were read on a Vmax kinetic microplate reader machine (Molecular Devices, Sunnyvale, CA). In some experiments, serum levels determined and tissue samples were harvested for further analysis. The HDM-induced allergic asthma model was performed, as described previously (20).

mDC preparation and induction of the allergic phenotype in vivo

Bone marrow (BM) cells were isolated from naïve BALB/c and C5L2-deficient mice by flushing femurs and tibias with ice-cold PBS. RBCs were lysed using Tris-ammonium chloride. BM cells were washed and then cultured at 2–3 × 106 cells/ml in complete RPMI 1640 culture medium and 20 mg/ml murine rGM-CSF (PeproTech, Rocky Hill, NJ). Cultures were incubated at 37°C in a humidified atmosphere containing 5% CO2 for 10 d. On day 9, cells were pulsed overnight with 30 μg/ml HDM (crude extract; Greer Laboratories, Lenoir, NC) in vitro. To induce pulmonary allergic phenotype in vivo, BM-derived HDM-pulsed DCs were harvested on day 10 and washed, and 1 × 102 DCs were injected i.t. into the airways of naïve BALB/c mice. Recipient mice were challenged once after 10 d with 100 μg/ml HDM i.t. Unpulsed DCs were injected into BALB/c recipients following the same protocol as controls. After 72 h, airway responsiveness was determined, and tissue as well as blood samples were harvested for further analysis.

Allergen-induced AHR

AHR was determined by measuring dynamic airway pressure (21) or by forced oscillation technique. Briefly, dynamic airway pressure was determined in anesthetized mice at the indicated time points after the final i.t. injection. Mice were intubated and ventilated at a rate of 120 breaths per minute with a constant tidal volume of air (0.2 ml), and paralyzed with 25 mg/kg weight of decamethonium bromide. After establishment of a stable airway pressure, 25 μg/kg weight of acetylcholine was injected i.v., and dynamic airway pressure measured as airway pressure time index in cm H2O × s−1 was followed for 5 min. Alternatively, airway resistance was measured in anesthetized mice that were mechanically ventilated using a FlexiVent (Scireq, Saint-Urbain, Quebec, Canada). Aerosolized metacholine (50 mg/ml; Sigma-Aldrich) was generated by ultrasonic nebulizer and delivered in-line through the inhalation port for 10 s and airway resistance was measured 2 min later.

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of OVA-specific IgE were assessed. Plates were coated with 50 μl OVA at a concentration of 10 μg/ml. Two-fold dilutions of mouse sera were then incubated in wells. OVA-specific IgE binding was detected in the same way, as described above.

**Lung histology**

Lung histological staining, detection, and quantification of mucus cell content were done, as described (15). Briefly, lungs were excised and fixed in 10% formalin. Fixed tissues were then washed with 70% ethanol, dehydrated, embedded in paraffin, and cut into 5-μm sections. Slides were stained with H&E and periodic acid-Schiff (PAS). For quantification of mucus production in the airway epithelium, PAS-positive and PAS-negative airways were counted by light microscopy for a total of four lung sections per animal. The percentages of PAS-positive airways were calculated.

**In vitro stimulation of BM mDCs**

BM-derived mDCs (1 × 10⁶/plate) were stimulated with HDM (30 μg/ml) in RPMI 1640 culture medium supplemented with 10% FBS, 2 mM l-glutamine, 100 U/ml penicillin, and 100 μg/ml streptomycin (all from Life Technologies Invitrogen) at 37°C for 72 h. Secretion of IL-1α, IL-6, IL-12p40, IL-12p70, IL-23, and TGF-β in culture supernatants was determined using DuoSet ELISA kits (R&D Systems) following the manufacturer’s protocol. The sensitivities were 16 pg/ml for IL-1α, IL-6, IL-12p40, IL-12p70, IL-23, and TGF-β, and 32 pg/ml for IL-23. Expression of surface co-stimulatory molecules was assessed by flow cytometry using fluorochrome-coupled Abs FITC anti-MHC class II (MHC-II), PE anti-CD86, PE anti-CD80, and PE anti-CD40, and appropriate FITC (MHC-II) or PE-labeled (CD86, CD80, and CD40) isotype controls (all from eBioscience, San Diego, CA); mDCs were identified as 7-aminocoumarin Dimer CD11c<sup>hi</sup> CD11b<sup>hi</sup> cells using a BD LSR II cell analyzer.

**Statistical analysis**

Statistical analysis was performed using the SigmaStat version 3.5 statistical package (Systat Software, Evanston, IL). Statistical difference of data was assessed by either ANOVA or unpaired t test. The p values <0.05 were considered statistically significant.

**Results**

**CSL2 deficiency results in a reduced asthmatic phenotype and Th2 adaptive immune responses in a mouse model of OVA-induced experimental allergic asthma**

CSa contributes to asthma pathogenesis through mechanisms involving CsaR signaling on APCs during allergen sensitization and myeloid effector cells during the allergic effector phase (3, 20). The role of the second receptor for CSA, CSL2, in asthma pathogenesis is less clear. To examine the role of CSL2 in the induction of pulmonary allergy as well as maladaptive Th2-biased immune responses, we focused on the frequently used model of OVA-induced allergic asthma (Fig. 1A). As expected, i.t. OVA challenge significantly enhanced AHR in WT mice as compared with PBS-treated controls. CSL2KOs on a BALB/c background also exhibited a marked increase in AHR upon OVA exposure; however, its magnitude was substantially lower as compared with WT littermates (Fig. 2A). Histological staining and cell differential analysis of BAL fluid showed marked reduction in OVA-induced pulmonary accumulation of inflammatory cells and mucus secretion in CSL2KOs as compared with WT mice (Fig. 2B, 2C, Table I). Furthermore, we observed reduced total BAL cell numbers and significantly reduced eosinophil and lymphocyte numbers in OVA-treated CSL2KOs as compared with WT controls. Neutrophils (Fig. 2B) and macrophage numbers (data not shown) were virtually indistinguishable between the two strains.

In addition to airway reactivity and inflammation, we also determined the impact of CSL2 deficiency on the development of maladaptive T and B cell responses in the OVA-induced asthma model. The i.t. OVA challenge enhanced the production of Th2 cytokines (IL-5, IL-13, IL-4, and IL-10) from pulmonary cells of both WT and CSL2KOs, which was associated with increased levels of serum total IgE and OVA-specific IgE. Importantly, serum IgE levels and pulmonary Th2 cytokine production were markedly attenuated in CSL2KOs as compared with WT mice (Fig. 2D, 2E). We did not detect any IFN-γ or IL-17 secretion from pulmonary cells of either strain (data not shown). Taken together, we demonstrate that mice with a defect in CSL2 show a reduced allergic phenotype as evidenced by decreased AHR, airway responsiveness, and mucus production, as well as decreased serum IgE responses following repeated pulmonary OVA exposure.

**CSL2 contributes to the expression of AHR and dysregulated Th2-polarized adaptive immunity in a mouse model of HDM-induced experimental allergic asthma**

In previous studies, controversial data have been generated regarding the role of ATs in different animal models of allergic asthma, which may result from differences in mouse strains and/or...
To exclude the possibility of an OVA-specific effect of C5L2 and to extend our studies to an allergen that frequently drives allergic asthma in humans (24), we next examined the impact of C5L2 deficiency on the development of HDM-induced allergic inflammation and pulmonary Th2 adaptive immunity (Fig. 1B). Similar to what we found in the OVA model, airway responsiveness was substantially increased in both WT and C5L2KOs upon i.t. HDM exposure. Importantly, C5L2KOs experienced significantly attenuated AHR when compared with WT littermates in response to either PBS or
C5L2-deficient mDCs have no impact on AHR, but show an impaired ability to drive B cell immunity and promote a complex Th1-, Th2-, and Th17-biased cytokine profile

Previous studies suggest a critical role of C5a in pulmonary DC-mediated T cell activation (3, 20, 27), with a prominent role for C5aR on plasmacytoid DCs, but not on mDCs (20). To investigate potential mechanisms underlying the distinct allergic response to pulmonary OVA exposure, we examined the development of adaptive immune responses. Th2 cytokine production (IL-5, IL-13, IL-4, and IL-10) from lung cells was markedly increased after adoptive transfer of HDM-pulsed mDCs as compared with unpulsed mDCs similar to what we had observed after i.t. HDM administration (Fig. 4E). Interestingly, we found some production of the prototypical cytokine of the Th1 lineage, i.e., IFN-γ in mice that had been exposed to HDM-loaded mDCs from WT mice, which was 4-fold higher after transfer of mDCs from C5L2-deficient mice (Fig. 4E). These findings suggest that C5L2 ligation in mDCs controls the differentiation and/or effector functions of Th1 cells in response to allergen exposure, at least in part. In contrast to Th2 and Th1 cytokine levels, which were higher after transfer of HDM-pulsed mDCs as compared with unpulsed mDCs, we found no differences in the magnitude of IL-17A production in response to transfer of HDM-pulsed or unpulsed mDCs (Fig. 4E), arguing against a specific role for allergen-induced IL-17 production after single mDC transfer. In contrast, we found a strong increase in IL-17A after repeated exposure to pulsed mDCs from C5L2−/−, but not from WT mice (Supplemental Figs. 1, 2A). This increase in IL-17A was associated with higher neutrophil numbers in BAL fluid (Supplemental Fig. 2B, 2C) similar to what we had observed after i.t. HDM administration into C5L2-deficient mice (Fig. 3B, 3D). Unfortunately, repeated adoptive transfer of DCs drives induction of T cell activation in the absence of HDM due to xenogeneic proteins present in PBS used in BM cell culture, as has been reported previously (28), which somewhat limits the significance of this approach.

When we evaluated the IgE response, we found a significant increase in IgE secretion in response to transfer of HDM-pulsed mDCs. Importantly, IgE levels in the C5L2 group were significantly lower than in the WT group (Fig. 4C), which is in agreement with the reduced IL-4 levels in this treatment group (Fig. 4E).

Table I. C5L2 deficiency results in reduced mucus production in response to pulmonary OVA exposure

<table>
<thead>
<tr>
<th>PAS-Positive Airways (%)</th>
<th>PBS Group</th>
<th>OVA Group</th>
<th>p Value</th>
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<tbody>
<tr>
<td>WT</td>
<td>1.9 ± 1.2</td>
<td>55.4 ± 4.1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C5L2KO</td>
<td>1.5 ± 1.5</td>
<td>35.5 ± 4.4</td>
<td>&lt;0.001</td>
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</table>

The quantification was assessed by determination of the percentages of PAS-positive airways from four lung histological sections of WT BALB/c mice and C5L2KOs in the OVA-induced asthma model. Values shown are the mean ± SEM; n = 8–10 per group. Values of p shown in table indicate statistical differences between PBS-treated and OVA-treated mice for each strain. p = 0.857 for comparison between PBS-treated WT and C5L2KOs; p = 0.008 for comparison between OVA-treated WT and C5L2KOs.
FIGURE 3. C5L2 deficiency results in reduced AHR and Th2 adaptive immune responses upon pulmonary HDM exposure. A, Airway responsiveness to i.v. acetylcholine. Airway responsiveness is expressed as the time-integrated change in airway pressure over baseline pressure. B, Total and differential cell counts in BAL fluid. Total cells (To), eosinophils (Eo), lymphocytes (Ly), and neutrophils (Ne). Differences in cell numbers are significant between the PBS group and the HDM group, unless otherwise indicated. C, Concentration of total IgE in serum. D, Histological examination of airway inflammation. Sections were stained with H&E (left panels) or for mucus production with PAS (right panels). Original magnification ×200; higher magnification for images at the upper left corner. E, Cytokine profile of pulmonary cells harvested from mice 72 h after the final in vivo HDM exposure. Supernatants were collected 72 h after in vitro cell culture. Values shown are the mean ± SEM; n = 7–10 per group; p values are indicated.
**CSL2 regulates HDM-driven IL-23 production from BM-derived mDCs**

To assess the mechanisms underlying the CSL2-mediated regulation of Th17 release in vivo, we determined the cytokine profile and the expression of MHC-II and of costimulatory molecules in WT and CSL2-deficient BM-derived mDCs stimulated in vitro with HDM. We focused on IL-1β, IL-6, and TGF-β, as these cytokines have been shown to drive Th17 differentiation (29), and on IL-23, which is critical for the maintenance of Th17 cells (30). IL-6 production from unpulsed CSL2-deficient mDCs was significantly enhanced as compared with WT mDCs (Fig. 5A). In the presence of HDM, IL-6 production from mDCs of either WT or CSL2-deficient mice increased substantially and reached similar levels (∼20 ng/ml). IL-1β production from WT or CSL2−/− mDCs was low in the absence of HDM. HDM stimulation resulted in clear IL-1β production from both strains, although IL-1β production from CSL2-deficient mDCs was significantly lower (Fig. 5B). Total TGF-β production from WT and CSL2-deficient DCs was high even in the absence of HMD stimulation and did not change following HDM stimulation. Of note, the overall TGF-β production from CSL2-deficient DCs was lower than that of WT DCs (Fig. 5C). Importantly, CSL2-deficient DCs, but not WT DCs, produced significant amounts of IL-23, which was associated with marked production of IL-12p40 (Fig. 5D, 5E), whereas IL-12p70 was below the detection limit (data not shown). Considered the increasing IL-17 production in response to repeated adoptive transfer of HDM-loaded mDCs from CSL2-deficient mice, these data suggest the regulatory impact of CSL2 is not related to the induction, but rather to the maintenance of Th17 cells.

**CSL2 regulates steady state MHC-II expression on BM-derived mDCs**

MHC-II, costimulatory molecules of the B7 family, and CD40 play important roles in mDC-mediated activation of naïve T cells in allergic asthma (31). As expected, we found only minor expression of MHC-II on WT mDCs under steady state conditions, which was not altered by HDM exposure. In contrast, MHC-II expression was 5-fold higher in CSL2-deficient mDCs (Fig. 6A). Again, HDM exposure did not change MHC-II expression. Similarly, we found a trend toward higher CD80 and CD86 expression on CSL2-deficient mDCs as compared with WT mDCs, both under steady state and under HDM-treated conditions (Fig. 6B, 6C), although the differences did not reach the level of statistical significance. CD40 expression also tended to be higher in CSL2-deficient mDCs, although this effect was observed only under steady state conditions (Fig. 6D). Taken together, our data indicate that CSL2 has a strong negative regulatory impact on steady state expression of MHC-II, but no obvious effect on B7 costimulatory molecule and CD40 expression.

**Discussion**

C5a exerts a Janus-faced function in allergic asthma, i.e., it protects from the development of maladaptive Th2 responses during allergen sensitization, but enhances the allergic phenotype during the effector phase (3). Specific targeting of the classical C5aR, CD88 (3, 32), as well as its targeted deletion (20) suggests a major role of this receptor in asthma development.

However, in the absence of C5aR, C5a and C5a-desArg can bind to CSL2, which has a similar cellular distribution to CD88 (7). To this end, little is known about the functional role of CSL2 in allergic asthma. CSL2-deficient mice generated by Chen et al. (14) have recently been evaluated in different models of acute inflammation, including a model of OVA-induced asthma. These mice showed reduced asthma-like AHR and airway inflammation, which has been assigned to the lack of proinflammatory C5a and C3a signals. In agreement with such data, we found in a distinct CSL2-deficient mouse strain (17) significantly reduced AHR and airway inflammation that was associated with decreased mucus production, Th2 cytokine production, and circulating allergen-specific IgE, suggesting a proinflammatory role for CSL2 in the development of allergic asthma similar to C3aR (22). Of note, in OVA-treated C3aR-deficient BALB/c mice, only airway reactivity was reduced, but not airway inflammation or Th2 cytokine production (23). In contrast, when C3aR-deficient C57BL/6 mice were sensitized with a combination of OVA and Aspergillus (22) or when BALB/c mice were immunized i.t. with HDM (20), Th2 adaptive immune responses were attenuated. Thus, CSL2 and C3aR appear to exert partially overlapping proallergic functions. This is in contrast to C5aR-deficient mice, which suffer from increased airway inflammation and Th2 cytokines in response to OVA (3). Recently, we have shown that the reduction of the allergic phenotype in C3aR-deficient mice results mainly from a dominant protective role of C5aR signaling in the C3aR-deficient mice (20). At this point, it is unclear whether the reduced phenotype in CSL2-deficient mice can be assigned to protective C5aR signaling or to the lack of CSL2 signaling by a pathway that is independent of G protein coupling (33).

In order to investigate the role of CSL2 in pulmonary allergy in a model closer to human asthma, we determined the functions of CSL2 in a HDM model induced by crude extracts from *Derma
tophagoides pteronyssinus*, which accounts for atopic symptoms in 10% of individuals with asthma (24). First, we noticed that the overall response following HDM sensitization was lower as compared with OVA sensitization. This effect may be due to presence of alum, which functions as a strong adjuvant during peritoneal OVA immunization (34). Secondly, we observed substantial differences in the allergic phenotype of CSL2-deficient mice immunized with OVA or HDM. Similar to the OVA model, CSL2 deficiency reduced AHR and the IgE response. In contrast to the OVA model, eosinophil and lymphocyte numbers were not affected by the absence of CSL2, whereas neutrophil counts in BAL were substantially higher in CSL2-deficient mice following HDM immunization. The differential pattern of cellular responses was recapitulated by the cytokine profile. Whereas IL-4, IL-10, and IL-13 levels were markedly reduced in CSL2−/− mice, IL-5 concentrations were indistinguishable between WT and CSL2−/− mice. Importantly, the increased neutrophil count in BAL of CSL2-deficient mice was associated with elevated IL-17A production from lung cells.

Our data suggest a complex proallergic role for CSL2 in HDM-mediated induction of pulmonary allergy. Extracts from HDM are known to promote allergic asthma via complex mechanisms, including TLR4 signaling on epithelial cells (35, 36) and direct ef-

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**Table II. CSL2 deficiency results in reduced mucus production in response to pulmonary HDM exposure**

<table>
<thead>
<tr>
<th></th>
<th>PBS Group</th>
<th>HDM Group</th>
<th>p Value</th>
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<tbody>
<tr>
<td>WT</td>
<td>0.74 ± 0.74</td>
<td>46.8 ± 2.48</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>CSL2KO</td>
<td>1.4 ± 0.87</td>
<td>39.2 ± 2.67</td>
<td>&lt;0.001</td>
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</table>

The quantification was assessed by determination of the percentages of PAS-positive airways from four lung histological sections of WT BALB/c mice and CSL2KOs in the HDM-induced asthma model. Values shown are the mean ± SEM; n = 7–10 per group. Values of p shown in table indicate statistical differences between PBS-treated and HDM-treated mice for each strain, p = 0.81 for comparison between PBS-treated WT and CSL2KOs; p = 0.031 for comparison between HDM-treated WT and CSL2KOs.
effects on DCs (37–39). Indeed, targeting of MyD88 or TLR4 decreased the magnitude of allergic airway responsiveness and inflammation (40) and TLR4 deficiency on airway structural cells reduced the development of asthma (41). Importantly, cross talk between TLRs and AT receptors has already been described (42). C5a enhances TLR4-mediated IL-6, TNF, and IL-1β secretion.
suppresses IL-12p40 production by a CD88-dependent mechanism in macrophages (43, 44). More specifically, C5a was shown to inhibit LPS-induced IL-12 family cytokine production, including IL-12 and IL-23 by ERK1/2 and PI3K-mediated signaling pathways (13). The role of C5L2 in C5a-mediated modulation of TLR responses is less clear. In contrast to the data from the Song laboratory (43), Chen et al. (14) reported that C5a can reduce LPS-driven TNF-α and IL-6 production from macrophages. This effect was absent in C5L2-deficient macrophages, suggesting that C5L2 affects C5a-mediated regulation of TLR4 responses. In support of this view, C5L2 promoted high mobility group box-1 production in a model of septic peritonitis and in vitro in neutrophils and peritoneal macrophages (19). The reduced asthmatic phenotype in C5L2 KO mice in response to HDM immunization may thus result from a reduction of a synergistic cross talk between TLR4 and C5L2.

The mDC population plays a key role in the Th2 polarization process following allergen encounter (45). Thus, we assessed whether the regulatory impact of C5L2 on Th2 immunity in HDM-mediated asthma results from a direct effect on mDCs. Our data that adoptive transfer of C5L2-deficient mDCs into WT mice results in decreased eosinophilic and lymphocytic inflammation and a decreased IgE response associated with slightly lower IL-4 suggest that C5L2 controls parts of the allergic phenotype through a regulatory impact on mDCs. Importantly, C5L2 deficiency in mDCs changed the pulmonary cytokine profile as compared with WT mDCs. In the absence of C5L2, mDCs were still able to drive profound production of Th2 cytokines; however, in contrast to their WT counterparts, C5L2 KO mDCs promoted the production of prototypical Th1 (IFN-γ) and, after repeated exposure to HDM-pulsed mDCs, Th17 (IL-17A) cytokines from lung cells, which was associated with increased neutrophil recruitment. These data suggest that the decreased Th2 cytokine production in response to i.t. HDM immunization does not result from a defect of C5L2 on mDCs, whereas the increased IL-17 production can be assigned to the lack of C5L2 on mDCs, at least after multiple allergen exposures. The impact of C5L2 on Th2 cytokine production may

### Table III. Pulmonary mucus production in response to adoptive transfer of HDM-stimulated mDCs from WT or C5L2-deficient mice

<table>
<thead>
<tr>
<th>PAS-Positive Airways (%)</th>
<th>Unpulsed Group</th>
<th>HDM-Pulsed Group</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>11.98 ± 2.18</td>
<td>44.2 ± 3.28</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C5L2KO</td>
<td>10.4 ± 1.25</td>
<td>36.8 ± 7.07</td>
<td>=0.001</td>
</tr>
</tbody>
</table>

The quantification was assessed by determination of the percentages of PAS-positive Airways from four lung histological sections of WT BALB/c mice and C5L2KO mice in the HDM-stimulated mDC adoptive transfer asthma model. Values shown are the mean ± SEM; n = 8–10 per group. Values of p shown in table indicate statistical differences between PBS-treated and HDM-treated mice for each strain. p = 0.789 for comparison between mice injected with HDM-unpulsed mDCs from WT versus C5L2 KO animals; p = 0.220 for comparison between mice injected with HDM-pulsed mDCs from WT versus C5L2 KO animals.

### FIGURE 5. C5L2-deficient mDCs promote the production of IL-23 in response to HDM stimulation.

BM cells that were differentiated in the presence of 10% FBS and 20 ng/ml murine rGM-CSF for 10 d were stimulated with 30 μg/ml HDM in complete RPMI 1640 culture medium. Supernatants were collected after 72 h of in vitro cell culture, and secretion of IL-6 (A), IL-1β (B), TGF-β (C), IL-23 (D), and IL-12p40 (E) in culture supernatants was determined using DuoSet ELISA kits. Values shown are the mean ± SEM; n = 3 per group; p values are indicated.
result from an effect on airway epithelial cells as they are critical for TLR-driven activation of the mucosal DC network in HDM-mediated asthma (35). Furthermore, epithelial cells can express C5L2 (10) and other complement factors (46). In human asthmatics and in HDM-treated mice, high concentrations of ATs have been described in BAL fluid (3, 47).

Our data further indicate that C5L2 on mDCs is critical to suppress the development of Th17 and Th1 cells. In support of this view, we found exclusive production of IL-23 in C5L2-deficient mDCs stimulated in vitro with HDM, which was absent in WT mDCs. Stable Th17 polarization is complex and requires two complementary pathways, as follows: first, the presence of at least IL-6 and TGF-β, which drive the initial differentiation of naïve CD4+ cells into Th17 cells, and secondly, the presence of IL-23, which is critical for full and sustained differentiation of this cell type (30). The missing impact of C5L2 deficiency on the major Th17-differentiating cytokine IL-6, associated with the strong impact on IL-23 and IFN-γ, suggests that the main role of C5L2 is to suppress the maintenance and sustained differentiation of Th17 cells and the induction of Th1 cells. In line with this view, we found the impact on allergen-dependent IL-17 production only after multiple i.t. allergen exposures with HDM or HDM-pulsed mDCs. In contrast, the direct effect of C5L2 on mDCs for the HDM-mediated induction of Th2 cells is at best minor.

The contribution of IL-17 to allergic asthma is complex (48, 49). In humans, several reports show elevated IL-17 production in asthmatics in particular in patients with severe asthma (50, 51), which correlates with neutrophil numbers (52, 53). In experimental asthma, IL-17 (54) and Th17 cells (25) have been shown to drive neutrophil recruitment into the airways, which is enhanced by IL-23 (55). In contrast, exogenous IL-17 was found to markedly reduce eosinophil counts in experimental asthma (49), which is in accordance with our findings of reduced eosinophilia in mice immunized with C5L2−/− mDCs. Interestingly, Wilson et al. (26) found modest Th2, but strong Th17 polarization and neutrophilia following airway immunization with OVA in the presence of low

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**FIGURE 6.** Increased MHC-II expression in C5L2-deficient mDCs. BM-derived mDCs were seeded 1 × 10^6/plate, and stimulated with HDM, 30 μg/ml, in complete RPMI 1640 culture medium. After 72 h, cells were analyzed for the expression of MHC-II (A) and the B7 costimulatory molecules CD80 (B) and CD86 (C), as well as for expression of CD40 (D). mDCs were identified as 7-aminoactinomycin D^neg/CD11chigh/CD11b^high cells. Values shown are the mean ± SEM; n = 3 per group; p values are indicated.
LPS. In contrast, the authors found strong Th2 polarization and eosinophilia in response to peritoneal OVA immunization with alum in C57BL/6 mice. Similarly, we observed predominant eosinophilia and strong Th2, but no Th17 immunity following peritoneal OVA immunization in the presence of alum in WT and C5L2-deficient BALB/c mice. In this context, the lack of C5L2 had no obvious impact on Th17 cell development. In contrast, airway immunization with crude HDM extract that contains substantial LPS resulted in modest Th2 cytokine production, but no IL-17. In this study, the absence of C5L2 mediated enhanced pulmonary neutrophil accumulation associated with IL-17 production. The differences with regard to the IL-17 production reported by Wilson et al. (26) and our data are likely to result from the different Ags (OVA’ LPS versus HDM + LPS) and the different mouse strains (C57BL/6 versus BALB/c) used. In fact, mite proteins play an important role in the development of asthma. For example, proteases from Dermatophagoides species can cleave C3 and C5 into their active fragments in vitro (56), and account for strong generation of C5a/C5a during allergen sensitization (3). The mechanisms underlying Th17 differentiation in asthma remain elusive. Our data suggest that complement receptor C5L2 on mDCs regulates Th17 differentiation following repeated HDM exposure in experimental allergic asthma.

In summary, our findings provide evidence for critical roles of C5L2 in the development of experimental allergic asthma through direct effects on mDCs as well as on other pulmonary cells. C5L2 exerts negative regulatory functions at the mDC/CDC4 T cell interface, thereby suppressing the development of Th1 and Th17 differentiation and the sustained pulmonary accumulation of neutrophils by an IL-23–dependent mechanism. This function is reminiscent of the effect of C5aR in spleen-derived DCs in which the lack of C5aR signaling resulted in increased Th17 differentiation of naive T cells in response to TLR2 stimulation (57). In contrast, C5L2 on other pulmonary cells is critical for the production of Th2 cytokines leading to AHR, eosinophilic inflammation, mucus production, and increased IgE production. Thus, C5L2 plays complex and dual roles in the pathogenesis of allergic asthma, which strongly suggest functions beyond a role as a decoy receptor for C5a/C5a-des-Arg.

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Disclosures

The authors have no financial conflicts of interest.

References


Supplemental data

Figure legends

Supplemental figure 1. Protocol underlying the model of experimental allergic asthma in response to repeated pulmonary exposure to HDM-pulsed mDCs. BM cells were harvested from WT BALB/c and C5L2-deficient mice. mDCs were generated by culturing BM cells in the presence of 10% FBS and 20 ng/ml recombinant murine GM-CSF for 10 days. On day 9, mDCs were pulsed overnight with HDM. One million mDCs were injected i.t. into BALB/c recipients the following day. The same treatment was repeated three times at the indicated time points. Twenty-four hours after the final injection, airway responsiveness was determined. Subsequently BAL fluid, blood samples, lung cells and tissues were collected for further analysis. BALB/c mice receiving unpulsed mDCs served as controls.

Supplemental figure 2. BM-derived C5L2−/− mDCs have an impaired ability to promote HDM-induced AHR, eosinophilic airway inflammation and B cell responses but drive IL-17, IFN-γ production associated with neutrophilic airway inflammation. (A) Cytokine profile of pulmonary cells harvested from mice 24 hours after the final adoptive cell transfer. Supernatants were collected 72 hours after in vitro cell culture. (B) Histological examination of airway inflammation. Sections were stained with H&E (left panels) or for mucus production with PAS (right panels). Original magnification, ×200; higher magnification for images at the upper left corner. (C) Total and differential cell counts in BAL fluid. To (Total cells), Eo (eosinophils), Ly (lymphocytes), Ne (neutrophils). (D) Concentrations of total IgE measured in serum. (E) Airway responsiveness to i.v. acetylcholine is expressed as the time-integrated change in airway pressure over baseline pressure. Values shown are the mean ± SEM; n = 10 per group; p values are indicated.
Zhang et al. Supplemental figure 1
Zhang et al. Supplemental figure 2
BM-derived WT and C5L2\textsuperscript{-/-} mDCs promote significant pulmonary mucus production in WT BALB/c mice. The quantification was assessed by determination of the percentages of PAS positive airways from four lung histological sections of WT BALB/c recipient mice. Values shown are the mean ± SEM; n=10 per group. \(p\)-values shown in the table indicate statistical differences between mice injected with HDM-unpulsed mDCs versus HDM-pulsed mDCs from each strain, i.e. WT and C5L2\textsuperscript{-/-} mice. \(p = 0.124\) for comparison between mice injected with HDM-unpulsed mDCs from WT versus C5L2\textsuperscript{-/-} animals. \(p = 0.267\) for comparison between mice injected with HDM-pulsed mDCs from WT versus C5L2\textsuperscript{-/-} animals.