

CRTH2 Plays an Essential Role in the Pathophysiology of Cry j 1-Induced Pollinosis in Mice¹

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PGD₂ is the major prostanoid produced during the acute phase of allergic reactions. Two PGD₂ receptors have been isolated, DP and CRTH2 (chemoattractant receptor-homologous molecule expressed on Th2 cells), but whether they participate in the pathophysiology of allergic diseases remains unclear. We investigated the role of CRTH2 in the initiation of allergic rhinitis in mice. First, we developed a novel murine model of pollinosis, a type of seasonal allergic rhinitis. Additionally, pathophysiological differences in the pollinosis were compared between wild-type and *CRTH2* gene-deficient mice. An effect of treatment with ramatroban, a CRTH2/T-prostanoid receptor dual antagonist, was also determined. Repeated intranasal sensitization with Cry j 1, the major allergen of *Cryptomeria japonica* pollen, in the absence of adjuvants significantly exacerbated nasal hyperresponsive symptoms, Cry j 1-specific IgE and IgG1 production, nasal eosinophilia, and Cry j 1-induced in vitro production of IL-4 and IL-5 by submandibular lymph node cells. Additionally, CRTH2 mRNA in nasal mucosa was significantly elevated in Cry j 1-sensitized mice. Following repeated intranasal sensitization with Cry j 1, *CRTH2* gene-deficient mice had significantly weaker Cry j 1-specific IgE/IgG1 production, nasal eosinophilia, and IL-4 production by submandibular lymph node cells than did wild-type mice. Similar results were found in mice treated with ramatroban. These results suggest that the PGD₂-CRTH2 interaction is elevated following sensitization and plays a proinflammatory role in the pathophysiology of allergic rhinitis, especially pollinosis in mice. *The Journal of Immunology*, 2008, 180: 5680–5688.

Pollinosis, a type of seasonal allergic rhinitis, is the most common allergic respiratory disease and is a global health problem that is increasing in prevalence (1–3). For example, as much as 10–20% of the Japanese population suffers from Japanese cedar pollinosis (JCP).³

Intensive and extensive studies on pollinosis have greatly improved the understanding of its etiology and pathology (4). Mouse models of allergic rhinitis have contributed to these advances. However, these mouse models usually use adjuvants and/or strong Ags to efficiently sensitize animals (5–9). To further examine the pathophysiological mechanism underlying pollinosis, a murine model that naturally mimics human pollinosis by intranasal ad-

ministration of pollen extracts in the absence of adjuvants is needed.

Prostanoids are thought to participate in allergic inflammation (10). PGD₂ is one of the most important of these and it plays roles in allergic respiratory diseases including allergic rhinitis (10–15). For example, nebulized PGD₂ enhances Th2-type inflammatory responses and eosinophilia, leading to the development of airway hyperresponsiveness (14). PGD₂ acts via the D-prostanoid receptor (DP) and chemoattractant receptor-homologous molecule expressed on Th2 cells (CRTH2) (16). The expression patterns and signaling pathways utilized by DP and CRTH2 are different, suggesting that they have distinct roles in allergic responses (16, 17). It appears that signals via DP promote eosinophil survival, whereas signals via CRTH2 mediate shape changes, chemotaxis, and degranulation by eosinophils (16, 18, 19).

The role of CRTH2 in allergic airway inflammation in vivo remains controversial (17). CRTH2 has been found to participate in the recruitment of eosinophils from the bone marrow into the bloodstream (19, 20), in eosinophilic airway inflammation (11), and in airway eosinophilia and hyperresponsiveness (21), suggesting that it plays a proinflammatory role in vivo. On the other hand, mice deficient for CRTH2 (*CRTH2*^{−/−}) show eosinophil recruitment and IL-5 production by splenocytes in an asthma model, suggesting that CRTH2 mediates antiinflammatory signals (22). In human nasal mucosa, CRTH2 is expressed in eosinophils and a subset of T cells (23). We have recently reported that there is a close correlation between the number of eosinophils infiltrating into nasal mucosa and the amount of CRTH2, but not DP, in nasal mucosa (12). Also, *CRTH2*^{−/−} mice have been found to show reduced eosinophil infiltration into skin in a model of chronic allergic skin inflammation (24).

In this study, we established a novel murine model of pollinosis and used it to determine the pathophysiological role of CRTH2 in

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³ Abbreviations used in this paper: JCP, Japanese cedar pollinosis; CRTH2, chemoattractant receptor-homologous molecule expressed on Th2 cells; DP, D-prostanoid receptor; TP, T-prostanoid receptor; WT, wild type.

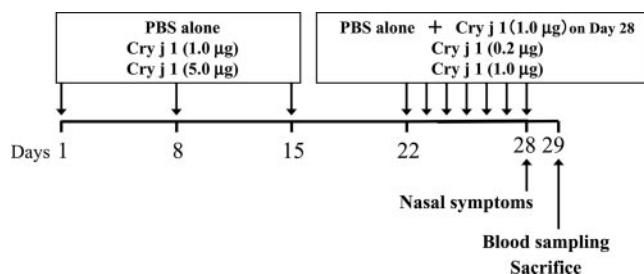


FIGURE 1. Experimental design used to investigate the effect of nasal exposure to Cry j 1 in mice. BALB/c mice (6–9 per group) were sensitized by intranasal administration of either 1.0 or 5.0 µg of Cry j 1 in 10 µl PBS in the absence of adjuvants once a week for 3 wk (on days 1, 8, and 15). One week after the third sensitization, mice were challenged by intranasal administration of one fifth Cry j 1, respectively every day for 7 consecutive days (on days 22 to 27). As a control, mice were treated with PBS, except for the final challenge, where mice were treated with 1.0 µg of Cry j 1. Immediately after the final nasal challenge, nasal symptoms were observed for 10 min, and 16 h after the final nasal challenge, peripheral blood was collected, and the specific Ab content in the serum was measured. After the blood sampling, mice were sacrificed, and the nose and submandibular lymph nodes were obtained for further analysis.

the disease. In this model, intranasal sensitization with Cry j 1, the major allergen of *Cryptomeria japonica* pollen, in the absence of adjuvant induced allergic rhinitis closely resembling human pollinosis. We found that a lack of CRTH2 in the mutant mice greatly reduces allergic pathophysiology in this model.

Materials and Methods

Animals and Ags

BALB/c mice were purchased from Charles River Laboratories Japan and CLEA Japan. Homozygous CRTH2-deficient and wild-type BALB/c mice were obtained as described previously (24). Female mice (7–11 wk old) were used in all the experiments. The mice were maintained in specific pathogen-free conditions at Okayama University and Tokyo Medical and Dental University in accordance with the guidelines set forth by the university committees. All experimental protocols and procedures in the present study were approved by the University Animal Care and Use Committees. Cry j 1 was purified from crude extracts of *C. japonica* pollen as described previously (25). Endotoxin contamination was considered to be negligible due to a negative result in the Endospec ES test (Seikagaku). Ramatroban was obtained from Bayer Yakuhin. Protein concentrations were determined using a bicinchoninic acid assay (Pierce) according to the manufacturer's instructions.

Sensitization of mice

Mice (6–9 animals per group) were sensitized by intranasal application of serial doses of Cry j 1 in 10 µl PBS in the absence of adjuvants using a microsyringe (Hamilton Medical). The low-dose sensitization consisted of a series of administrations of 1.0 µg of Ag once a week for 3 wk (on days 1, 8, and 15), followed by administration of 0.2 µg Ag every day for 7 consecutive days (on days 22 to 28). For high-dose sensitization, 5.0 and 1.0 µg of Cry j 1 were administered once a week for 3 wk (on days 1, 8, and 15) and every day for 7 consecutive days (on days 22 to 28), respectively. As a control, mice were treated with PBS instead of the Ag at all points except for the final challenge, where the mice were administered 1.0 µg of Cry j 1 (Fig. 1). Immediately after the final nasal challenge, the frequencies of sneezing and nasal rubbing were counted in a blinded manner for 10 min. Peripheral blood was collected from the tail vein 16 h after the final nasal challenge, and then sera were prepared by centrifugation at 200 × g, and the levels of Cry j 1-specific Ab in the serum were determined by ELISA. The mice were then sacrificed, and the nose and submandibular lymph nodes were isolated for further immunological and histological analyses.

To determine whether the effect of CRTH2 deficiency is at the level of sensitization or amplification of allergic cascade, outcomes of pollinosis were compared with CRTH2^{-/-} mice sensitized and subsequently challenged with Cry j 1 and nonsensitized CRTH2^{-/-} mice with a single challenge with Cry j 1.

Ramatroban treatment

Ramatroban was suspended in 5% methyl cellulose and administered orally at a dose of 30 mg/kg body weight once a day from 1 day before the first sensitization to the final challenge (day 0 to day 28). Control mice were given 5% methyl cellulose alone.

Ab determination

The levels of Cry j 1-specific IgE, IgG1, and IgG2a were determined by ELISA as previously described (26). The levels of Cry j 1-specific IgE were measured using biotinylated Cry j 1 (Hayashibara Biochemical Laboratories) as a detecting reagent. The titers of Ag-specific Abs were estimated according to the mean OD at 450 nm of serum dilutions of 1/20 for IgE and 1/100 for IgG1 and IgG2a.

In vitro culture of submandibular lymph node cells and measurement of cytokine production

Submandibular lymph nodes from mice were dispersed and filtered through a 70-µm cell strainer (BD Biosciences) to yield a single-cell suspension. Lymph node cells were suspended in RPMI 1640 supplemented with 10% heat-inactivated FCS (Invitrogen), 100 µg/ml streptomycin, 100 U/ml penicillin, and 20 mM L-glutamine (Sigma-Aldrich). Cells (4×10^5 cells/200 µl) were cultured in the presence or absence of 10 µg/ml Cry j 1 in 96-well flat-bottom plates (BD Biosciences) at 37°C in humidified atmosphere of 5% CO₂ and 95% air. After 72 h of culture, supernatants were harvested. The levels of IL-4, IL-5, and IFN-γ in the culture supernatant were measured using OptEIA sets (BD Biosciences). The levels of IL-13 were measured using DuoSet ELISA development kit (R&D Systems). The detection limits for IL-4, IL-5, IL-13, and IFN-γ in this system were 10, 30, 40, and 60 pg/ml, respectively.

Histological examination

Histological examination was performed as previously described (26). Coronal nasal sections were stained with H&E and Luna solution to detect mononuclear cells and eosinophils, respectively. A blind test was conducted to determine the numbers of infiltrating cells in the posterior part of nasal septum using a high-power (10×40) microscopic field.

To determine the infiltration of T cells into nasal mucosa, immunohistochemistry for CD3 was examined. Paraffin-embedded nasal tissues were sectioned into 5-µm slices, deparaffinized, rehydrated and retrieved with microwave. Endogenous peroxidase activity was quenched with 3% H₂O₂, and nonspecific protein binding was blocked with normal rabbit serum (DAKO Japan) for 60 min. After this, the tissue sections were incubated with goat anti-mouse CD3-ε polyclonal Ab (sc-1127; Santa Cruz Biotechnology) or control goat IgG Ab (M-20; Santa Cruz Biotechnology) overnight at 4°C. To detect the reaction, N-Histofine Simple Stain MAX PO (G) (Nichirei Biosciences) and diaminobenzidine substrate (DAKO Japan) was used according to the manufacturers' instructions.

Real-time quantitative PCR in nasal mucosa

Mucosal tissues were removed from nasal septum 16 h following the final nasal challenge, immediately soaked in buffer containing guanidine isothiocyanate from the RNeasy Mini Kit (Qiagen), and stored at -80°C until use. Extraction of total cellular RNA, reverse transcription to generate cDNA, and real-time quantitative PCR were performed using a Chromo4 Real-Time PCR detector (Bio-Rad Laboratories, Hercules) and QuantiTect SYBR Green PCR reagents (Qiagen) as described previously (12). The primer sequences for CRTH2 and GAPDH are shown in Table I. Standard curves for both CRTH2 and GAPDH were generated using a PCR fragment of CRTH2 and plasmid DNA of GAPDH as a standard, respectively. Then absolute copy number of CRTH2 and GAPDH for each sample was calculated, and samples were reported with a CRTH2 copy number relative to GAPDH.

Relative amounts of IL-4, IL-5, IL-13, IFN-γ, IL-1β, IL-6, TNF-α, RANTES, and eotaxin mRNA in nasal mucosa were also measured. The primers used are listed in Table I.

Statistical analysis

Statistical significance was determined by nonparametrical Mann-Whitney *U* tests. *p* values of <0.05 were considered to indicate statistical significance. Values are shown as means ± SEM.

Table I. Primary sequences used for real-time PCR amplifications

	Forward Primer	Reverse Primer	Amplification Size (bp)	Genbank Accession No.
IL-4	CCTCACAGCAACGAAGAACA	CTGCAGCTCCATGAGAACAC	133	NM_021283
IL-5	TCAGCTGTGTCTGGGCACT	TTATGAGTAGGGACAGGAAGCCTCA	133	NM_010558
IL-13	TGCTTGCTTGGTGGTCTC	CAGGTCCACACTCCATACC	151	NM_008355
IFN- γ	GCGTCATTGAATCACACCTG	ACCTGTGGGTTGTTGACCTC	103	NM_008337
IL-1 β	TCCAGGATGAGGACATGAGCAC	GAACGTACACACAGCAGGTTA	105	NM_008361
IL-6	CCACTTCACAAGTCGGAGGCTTA	GCAAGTGCATCATCGTTGTTTCATAC	112	NM_031168
TNF- α	ATGAGCACAGAAAGCATGATC	TCCACTTGGTGGTTTGTCTACG	305	NM_013693
RANTES	AGATCTCTGCAGCTGCCCTCA	GGAGCACTTGTCTGCTGGTGTAG	170	NM_013653
Eotaxin	CAGATGCACCTGAAAAGCCATA	TGCTTTGTGGCATCTCTGGAC	96	NM_011330
CRTH2	TCTCAACCAATCAGCACACC	CCTCCAAGAGTGGACAGAGC	173	NM_009962
GAPDH	ACCACAGTCCATGCCATCAC	TCCACCACCTGTGTCTGTA	452	NM_008084

Results

Induction of nasal symptoms in Cry j 1-sensitized mice

We first attempted to generate a mouse model mimicking human allergic rhinitis, especially pollinosis, which causes symptoms of nasal symptoms, including sneezing and nasal rubbing, by intranasal administration of Cry j 1. We found a significant and dose-dependent increase in the frequency of sneezing in BALB/c mice sensitized with Cry j 1. Mice that were treated with PBS alone sneezed 1.8 ± 0.3 (mean $\pm$ SEM) times in the 10 min following the final Ag administration, whereas they sneezed 5.8 ± 1.2 times and 15.7 ± 2.7 times when treated with low and high doses of Ag, respectively (Fig. 2A). Similarly, immediately after the final Ag challenge, nasal rubbing was observed more frequently in mice sensitized with a high dose of Cry j 1 than in control mice (37.3 ± 5.8 vs 11.2 ± 2.7 times in 10 min). At a low dose of Cry j 1, there was no significant increase in the frequency of nasal rubbing (Fig. 2B).

Development of Th2-type immune responses in Cry j 1-sensitized mice

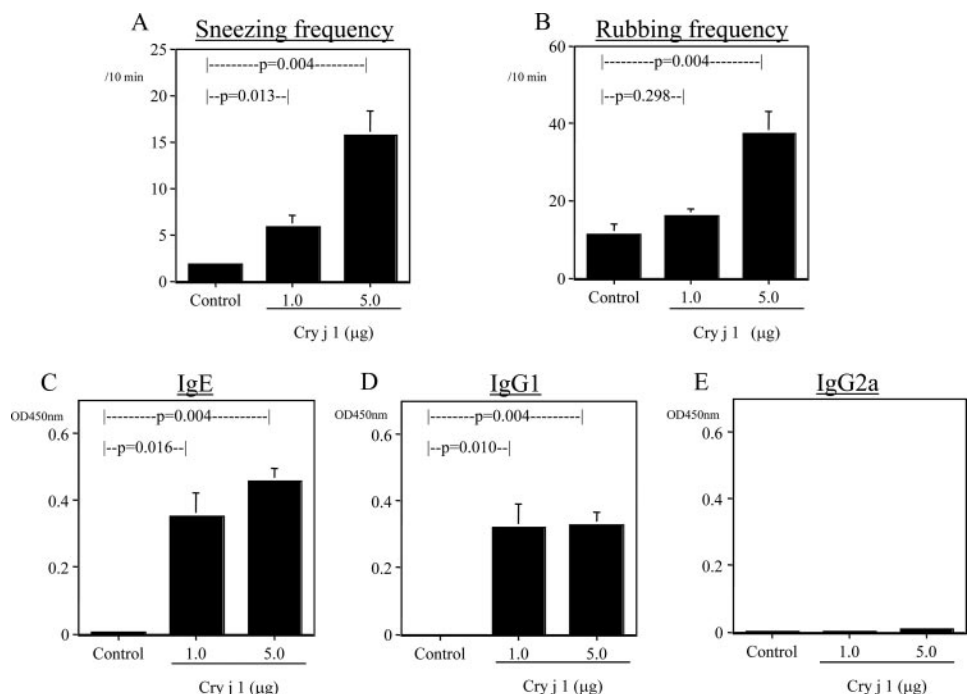
To further characterize the pathogenesis of immune responses caused by Cry j 1, we monitored several parameters associated with pollinosis. Nasal challenge with a low or high dose of Cry j

1 caused a considerable increase in the concentration of Cry j 1-specific IgE in sera when measured 1 day after the final challenge (Fig. 2C). There was also a significant elevation in the concentration of Cry j 1-specific IgG1 (Fig. 2D). The concentration of Cry j 1-specific IgE and IgG1 was not appreciably different at the low and high doses of Cry j 1. Cry j 1, however, had little effect on the level of Cry j 1-specific IgG2a (Fig. 2E).

Eosinophil infiltration into nasal mucosa, another characteristic of pollinosis, is rarely seen in the nasal mucosa in control mice (Fig. 3A). On the contrary, there was a marked accumulation of eosinophils not only in the lamina propria but also in the epithelial layer in mice 1 day after the final challenge (Fig. 3, B and C). Eosinophil numbers per field following intranasal Cry j 1 sensitization/challenge at both low and high doses were significantly higher than in control mice (Fig. 3D). The nasal mucosa of Cry j 1-sensitized mice also showed severe infiltration by mononuclear cells. The nasal septum of mice treated with low and high doses of Cry j 1 contained more mononuclear cells per field (59.8 ± 9.0 ($p = 0.055$) and 80.2 ± 9.1 ($p = 0.016$), respectively) than did control mice (39.8 ± 4.7).

We next examined the in vitro production of cytokines in culture by cells isolated from submandibular lymph nodes from mice treated in vivo with or without Cry j 1. The amounts of IL-4 and

FIGURE 2. Nasal hyperresponsive symptoms and Ab production in mice following intranasal sensitization and challenge with Cry j 1. Mice were sensitized and challenged by intranasal administration of Cry j 1. Nasal allergic symptoms, including the frequency of sneezing (A) and rubbing (B), were determined for the 10 min immediately following the final nasal challenge (day 28). Mean frequencies $\pm$ SEM are shown. Serum samples were obtained 16 h after the final intranasal challenge. Cry j 1-specific IgE (C), IgG1 (D), and IgG2a (E) levels were determined by ELISA. Mean OD values $\pm$ SEM are shown. Results are representative of two independent experiments.



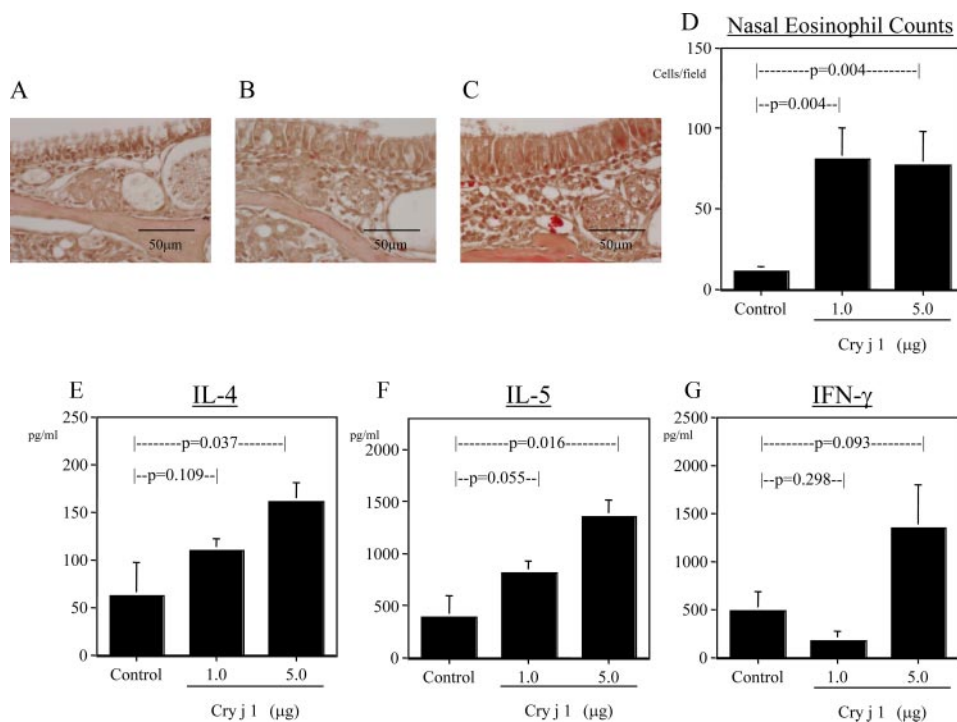


FIGURE 3. Nasal eosinophilia and cytokine production by submandibular lymph node cells following intranasal sensitization and challenge with Cry j 1. Mice were sensitized and challenged by intranasal administration of PBS (A), low-dose Cry j 1 (B), or high-dose Cry j 1 (C) according to the schedule shown in Fig. 1. Sixteen hours after the final challenge, nasal sections were collected, fixed, and decalcified, and eosinophils in the nasal mucosa were detected by Luna stain. D, The numbers of eosinophils in the posterior portion of the nasal septum were determined per high-power (10×40) microscopic field. Mean numbers of infiltrating cells per field $\pm$ SEM are shown. Sixteen hours after the final challenge, submandibular lymph node cells were isolated and cultured in the absence or presence of Cry j 1 for 72 h. IL-4 (E), IL-5 (F), and IFN- γ (G) were measured by ELISA. Mean concentrations $\pm$ SEM are shown. Results are representative of two independent experiments.

IL-5 produced by the cells were in proportion to the doses used for in vivo sensitization (Fig. 3, E and F). IFN- γ production was slightly enhanced in lymph node cells from mice treated with a high dose of Cry j 1 compared with control mice, but the increase was not statistically significant (Fig. 3G).

CRTH2 mRNA expression in nasal mucosa of Cry j 1-sensitized mice

We next measured the expression of CRTH2 at sites of nasal inflammation. Control mice treated with PBS expressed a low level of CRTH2 mRNA in the mucosal tissue of the nasal septum. In mice treated with Cry j 1, the level of CRTH2 mRNA was significantly increased (Fig. 4). Thus, we further investigated whether CRTH2 is positively or negatively involved in the pathophysiology of pollinosis using CRTH2^{-/-} mice.

Impaired pathophysiology of pollinosis in Cry j 1-sensitized CRTH2^{-/-} mice

A high dose of Cry j 1 was administered to both wild-type (WT) and CRTH2^{-/-} mice, and the nasal hyperresponsive symptoms were examined immediately after the final nasal challenge. Notably, the number of sneezes in 10 min by the Cry j 1-sensitized mutant mice was significantly lower than by the WT mice (Fig. 5A). Nasal rubbing was also significantly lower in the CRTH2^{-/-} mice than in the WT mice (Fig. 5B).

The level of Cry j 1-specific IgE in serum samples collected on the day following the final Ag challenge was significantly lower for mutant mice than for WT mice (Fig. 5C). Production of Cry j 1-specific IgG1 was similarly reduced in CRTH2^{-/-} mice compared with WT mice (Fig. 5D). In contrast, serum levels of Cry j 1-specific IgG2a were the same in the two mouse strains (Fig. 5E).

The number of eosinophils infiltrating into the nasal septum following administration of Cry j 1 was also significantly lower in the CRTH2^{-/-} mice than in the WT mice (Fig. 6A–C). Although the number of mononuclear cells infiltrating the nasal septum was not significantly different in the mutant and WT mice (Fig. 6D), the number of infiltrating CD3⁺ cells was significantly reduced in CRTH2^{-/-} mice as compared with WT mice (Fig. 6E). These

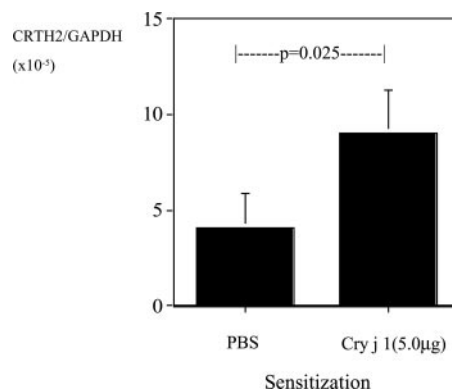
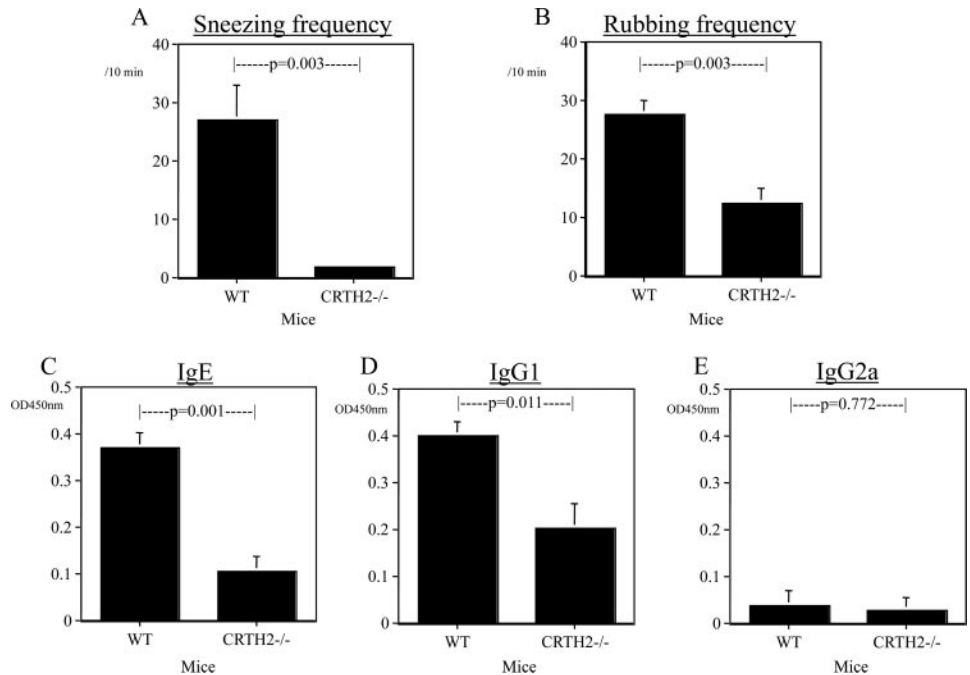


FIGURE 4. Relative amounts of CRTH2 mRNA in nasal mucosa. Mice (6 per group) were sensitized by intranasal administration of 5.0 μg of Cry j 1 once a week for 3 wk. One week after the third sensitization, mice were challenged by intranasal administration of 1.0 μg of Cry j 1 each day for 7 consecutive days. Control animals were treated with PBS at all steps except for the final challenge, where they were treated with 1.0 μg of Cry j 1. Sixteen hours after the final challenge with Cry j 1, mucosal tissues were removed from the nasal septum. The CRTH2 mRNA levels were estimated using real-time quantitative PCR. Results are the mean amounts of mRNA $\pm$ SEM.

FIGURE 5. Nasal symptoms and Ab production in WT and CRTH2^{-/-} mice following the final nasal challenge with Cry j 1. Mice were sensitized and challenged by intranasal administration of Cry j 1. Sneezing (A) and rubbing (B) frequency were measured for 10 min following the final nasal challenge (day 28). Mean frequencies $\pm$ SEM are shown. Sixteen hours after the final nasal challenge, blood was sampled from mice, and levels of serum Cry j 1-specific IgE (C), IgG1 (D), and IgG2a (E) were determined by ELISA. Mean ODs $\pm$ SEM are shown. Results are representative of two independent experiments.



results suggest that CRTH2 deficiency affects infiltration of not only eosinophils but also T cells.

To clarify the link between CRTH2 deficiency and the relief of allergic symptoms, we further investigated cytokine production *in vitro* by cells from submandibular lymph nodes obtained the day after the final Ag challenge. The amount of IL-4 was 5-fold lower in CRTH2^{-/-} mice than in WT mice (Fig. 6F). Additionally, there was a slight reduction in the amount of IL-5 (Fig. 6G) and a slight

increase in the amount of INF- γ (Fig. 6I) in the cells from CRTH2^{-/-} mice, but the differences were not significant. On the contrary, the levels of IL-13 were significantly higher in CRTH2^{-/-} mice as compared with WT mice (Fig. 6H).

Additionally, mRNA levels of Th2 cytokines (IL-4, IL-5, and IL-13), Th1 cytokine (INF- γ), proinflammatory cytokines (IL-1 β , IL-6 and TNF- α), and eosinophil-chemotactic chemokines (RANTES and eotaxin) in nasal mucosa were determined. The

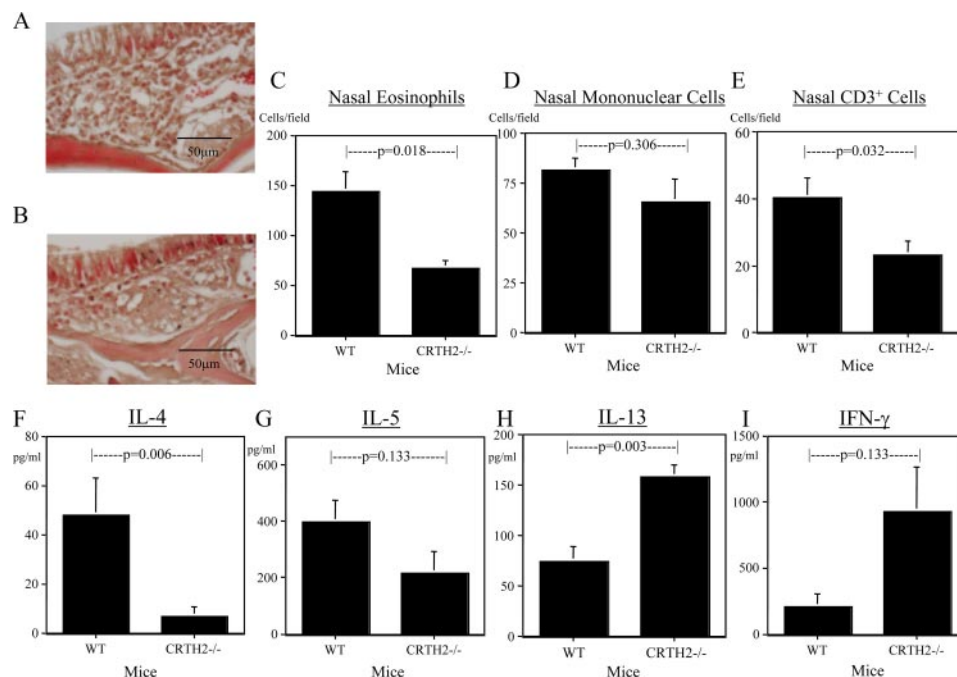
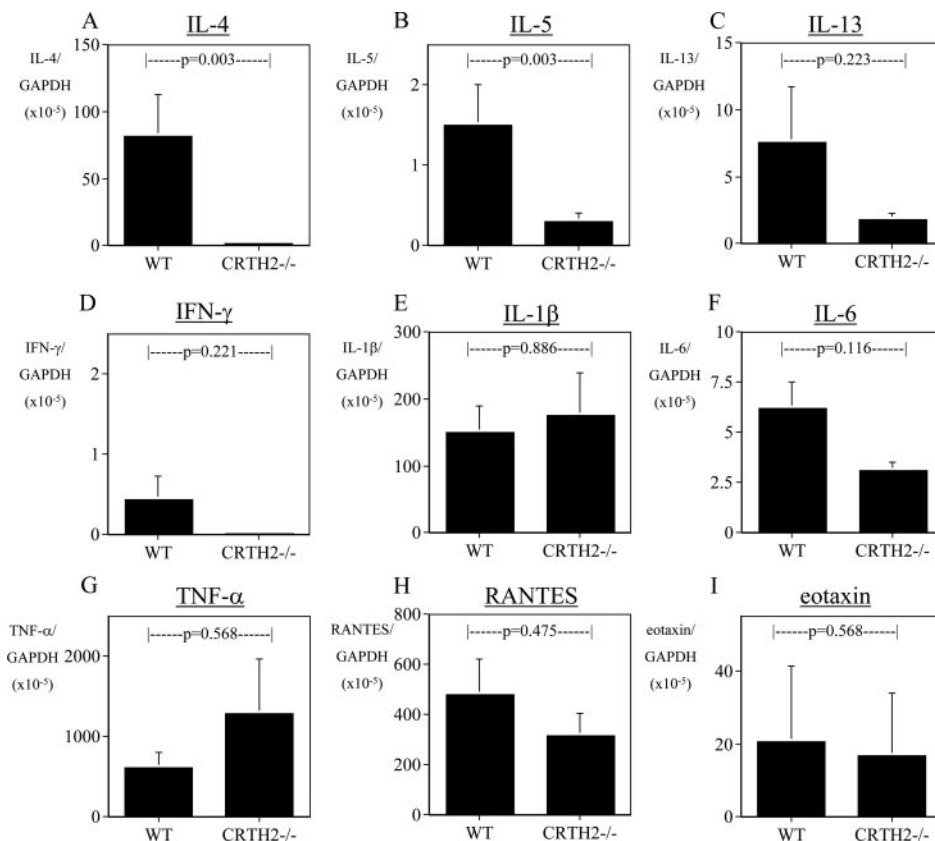


FIGURE 6. Histological changes and cytokine production by submandibular lymphocytes following nasal challenge with Cry j 1 in WT and CRTH2^{-/-} mice. WT (A) and CRTH2^{-/-} (B) mice were sensitized and challenged by intranasal administration of Cry j 1. Sixteen hours following the final nasal challenge with Cry j 1, nasal sections were collected, fixed, and decalcified, and eosinophils in nasal mucosa were detected by Luna stain. C, The number of eosinophils in the posterior portion of the nasal septum was determined per high-power (10 $\times$ 40) microscopic field. Mean numbers of infiltrating eosinophils per field $\pm$ SEM are shown. Numbers of mononuclear cells (D) and CD3⁺ cell (E) in the nasal septum were also determined. Sixteen hours after the final challenge with Cry j 1, submandibular lymph node cells were isolated and cultured with Cry j 1 for 72 h. IL-4 (F), IL-5 (G), IL-13 (H), and INF- γ (I) were measured by ELISA. Mean concentrations $\pm$ SEM are shown. Results are representative of two independent experiments.

FIGURE 7. Relative amounts of cytokines/chemokines mRNA in nasal mucosa following nasal challenge with Cry j 1 in WT and CRTH2^{-/-} mice. Sixteen hours after the final nasal challenge with Cry j 1, mucosal tissues were removed from nasal septum. Relative amounts of IL-4 (A), IL-5 (B), IL-13 (C), IFN- γ (D), IL-1 β (E), IL-6 (F), TNF- α (G), RANTES (H), and eotaxin (I) mRNA were compared between WT and CRTH2^{-/-} mice. Results are the mean amounts of mRNA $\pm$ SEM.



levels of IL-4 and IL-5 mRNA were significantly lower in CRTH2^{-/-} mice as compared with WT mice, whereas the levels of other cytokines/chemokines were similar between CRTH^{-/-}

and WT mice (Fig. 7). These results suggest that reduced nasal eosinophilia in CRTH2 deficiency is associated with reduced levels of IL-5 but not RANTES or eotaxin in this model. Additionally,

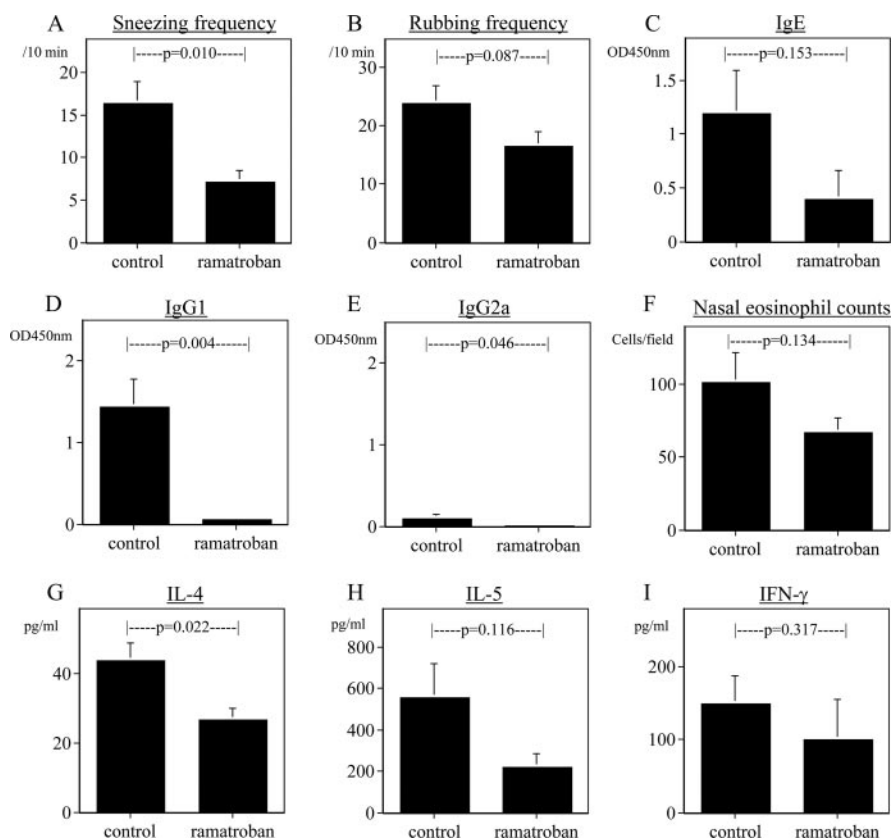


FIGURE 8. Effects of ramatroban on murine JCP. Ramatroban (30 mg/kg body weight), suspended in 5% methyl cellulose, was given orally once a day from 1 day before the first sensitization to the final challenge (day 0 to day 28). Control mice were given 5% methyl cellulose alone. After the final intranasal challenge, the frequencies of sneezing (A) and rubbing (B) were counted, and serum levels of Cry j 1-specific IgE (C), IgG1 (D), IgG2a (E), and nasal eosinophil count (F), as well as Cry j 1-induced IL-4 (G), IL-5 (H) and IFN- γ (I) were determined as described in *Materials and Methods*. Results are expressed as means $\pm$ SEM.

it is suggested that CRTH2-mediated pathway may induce pathology without regulating local production of these proinflammatory cytokines.

Outcomes of pollinosis were compared between sensitized/challenged CRTH2^{-/-} mice and nonsensitized/single-challenged CRTH2^{-/-} mice. The levels of Cry j 1-specific IgE (0.159 ± 0.044 vs 0 ± 0 OD at 450 nm; $p = 0.003$), Cry j 1-specific IgG1 (0.638 ± 0.163 vs 0 ± 0 OD at 450 nm; $p = 0.004$), nasal eosinophilia (66.4 ± 8.2 vs 6.6 ± 1.1 cells/field; $p = 0.005$), and IL-4 production by submandibular lymph node cell (72.8 ± 31.1 vs 6.7 ± 3.8 pg/ml; $p = 0.004$) were significantly higher in sensitized and subsequently challenged CRTH2^{-/-} mice as compared with nonsensitized and single-challenged CRTH2^{-/-} mice. However, the frequencies of sneezing (1.7 ± 0.5 vs 0.6 ± 0.2 times in 10 min; $p = 0.088$) and rubbing (12.3 ± 2.6 vs 10.2 ± 3.1 times in 10 min; $p = 0.516$) were similar between two groups, suggesting that CRTH2 is particularly essential for the development of nasal symptoms.

Effect of ramatroban on Cry j 1-induced pollinosis

As seen in CRTH2-deficient mice, treatment with ramatroban significantly reduced several indicators of pollinosis including sneezing, Cry j 1-specific IgG1 production, and Cry j 1-induced IL-4 production by submandibular lymph node cells as compared with the control treatment (Fig. 8, A, D, and G). Although the differences did not reach to the statistical level, other parameters such as nasal rubbing, Cry j 1-specific IgE production, nasal eosinophilia, and Cry j 1-induced IL-5 production were also reduced by the treatment with ramatroban (Fig. 8, B, C, F, and H).

Discussion

In the present study, we analyzed the pathophysiological effects of nasal exposure to Cry j 1 in BALB/c mice. Mice sensitized with Cry j 1 without adjuvants showed not only allergic symptoms such as sneezing and rubbing but also produced Cry j 1-specific IgE and IgG1 and displayed nasal eosinophilia. Additionally, submandibular lymph node cells isolated from these mice produced IL-4 and IL-5 in recall response to Cry j 1. These results suggest that intranasal sensitization with Cry j 1 induces pollinosis in BALB/c mice.

To investigate the initiation of allergic rhinitis in vivo, administration of Ags via the natural route (i.e., through the nostril) is desirable. In fact, it is known that administration of Ags through different routes results in different degrees of IgE production (27, 28). Also, murine models of allergic rhinitis have been generated by intranasal or aerosol-mediated sensitization (8, 29), but these models generally employ adjuvants such as cholera toxin, which have immunoregulatory effects that may distort the physical sensitization (30, 31). Therefore, we and others have established murine models of allergic rhinitis by intranasal sensitization with Ags including *Schistosoma mansoni* egg Ag, phospholipase A₂ from honeybee venom, extracts of *Aspergillus fumigatus*, OVA, and trimellitic anhydride in the absence of adjuvants (5–7, 9, 32). We think that our current model is the first in which murine pollinosis was induced by intranasal sensitization with pollen allergen in the absence of an adjuvant. This model may be useful not only for understanding the pathophysiology of pollinosis but also for developing and/or testing new therapies for allergic rhinitis, especially JCP.

BALB/c mice sensitized with Cry j 1 showed an increase in the expression of CRTH2 mRNA in the nasal septum compared with control mice. This agrees with our recent report demonstrating that the amount of CRTH2 mRNA in nasal mucosa is significantly higher in patients with allergic rhinitis than in control subjects not

showing hypertrophy of inferior turbinates (12). These results suggest that the expression of CRTH2 may play a role in the pathogenesis of allergic rhinitis both in humans and in mice. In fact, it is known that the expression of CRTH2 in eosinophils and CD4⁺ T cells is elevated in atopic patients (33–35). CRTH2 is expressed by eosinophils and a subset of CD3⁺ T cells in nasal mucosa, especially in patients with allergic rhinitis (23). Because a mAb against murine CRTH2 that can be used for immunohistochemistry is not currently available, we could not investigate the phenotype of cells expressing CRTH2 in mice.

The pathophysiology of allergic rhinitis was clearly impaired in CRTH2^{-/-} mice. Following repeated intranasal sensitization and nasal challenge with Cry j 1, CRTH2^{-/-} mice displayed reduced nasal symptoms, production of Cry j 1-specific IgE and IgG1, and nasal eosinophilia compared with WT mice. Additionally, submandibular lymph node cells from Cry j 1-sensitized CRTH2^{-/-} mice produced significantly less IL-4 and IL-5 in response to Cry j 1 than those from WT mice. We think that the present results are the first demonstration of the in vivo role of CRTH2 in the initiation of Th2 responses in the upper airway.

We also found that Cry j 1-specific IgE and IgG1 but not IgG2a production was impaired in CRTH2^{-/-} mice. Ag-specific IgE/IgG1 and IgG2a production is known to be positively regulated by Th2 and Th1 responses, respectively, in mice (36). Thus, our results indicate that signals mediated by CRTH2 selectively enhance Th2-type Ab production. The decreased production of IL-4 by submandibular lymph node cells from CRTH2^{-/-} mice in response to Cry j 1 restimulation supports this result because IL-4 plays a critical role in IgE synthesis in vivo (37). Although whether CRTH2 activation directly leads to IL-4 production in mice remains unclear, recent investigations have demonstrated that PGD₂ causes the preferential induction of IL-4 production by Th2 cells in humans by binding to CRTH2 (38, 39). Additionally, our recent report showing that CRTH2 signals up-regulate CD40L in resting human Th2 cells supports our conclusions because the engagement of CD40 by CD40L is also essential for IgE isotype switching (39, 40).

After intranasal sensitization with Cry j 1, CRTH2^{-/-} mice developed a weaker eosinophilia than did WT BALB/c mice. This suggests that CRTH2 mediates local eosinophil recruitment in this model, which agrees with reports showing that CRTH2 activation leads to changes in eosinophil shape, chemotaxis, and degranulation in vitro (16, 18, 41). Additionally, recent investigations have revealed that CRTH2 plays a proinflammatory role in eosinophil chemotaxis into inflamed tissue in vivo (11, 12, 21, 24, 42). On the other hand, submandibular lymph node cells from WT and CRTH2^{-/-} mice produced similar amount of IL-5 after intranasal sensitization with Cry j 1. It is well known that IL-5 plays a critical role in eosinophilic inflammation, especially in mice (43). Although little is known about whether CRTH2 activation enhances IL-5 production in mice, CRTH2 activation on Th2 cells is known to induce IL-5 production in humans (38, 39). One explanation of why nasal eosinophilia was reduced in CRTH2^{-/-} mice irrespective of IL-5 production is that cognate interaction between PGD₂ and CRTH2 on eosinophils may have an additive effect on local eosinophil recruitment, primarily due to the action of IL-5. In fact, in a mouse model of asthma, nebulized DK-PGD₂, a CRTH2 agonist, exacerbates eosinophilic lung inflammation without changes in IL-5 content in lung (21).

CRTH2^{-/-} mice displayed a significantly lower frequency of both sneezing and nasal rubbing after the nasal challenge compared with the WT mice. Several molecules, including IL-5, CD80/CD86, H1, and CD39, have been shown to contribute to these symptoms via different mechanisms (38, 44–46). The present result suggests that activation of CRTH2 is also involved

in the symptoms of nasal hyperreactivity. In humans, nasal challenge with PGD₂ induces a sustained nasal obstruction but not sneezing or rhinorrhea (47). Whether murine mast cells express CRTH2 is not well known, and further investigations are needed to determine whether the effect of CRTH2 on nasal hyperreactivity is due to the control of Th2 responses or to a direct effect on mast cells.

Treatment with ramatroban, a CRTH2/TP dual antagonist, induced a reduction in several indicators of JCP such as sneezing, Cry j 1-specific IgG1 production, and Cry j 1-induced IL-4 production. It is known that ramatroban suppresses allergic responses including nasal signs both in vivo and in vitro (11, 24, 46, 48). For example, ramatroban significantly inhibited sneezing and nasal rubbing induced by Ag in actively sensitized C57BL/6 mice and guinea pigs (46, 48). Our present results are consistent with these reports and support the findings seen in CRTH2^{-/-} mice that suggest a proinflammatory role of CRTH2 in allergic rhinitis. On the other hand, treatment with ramatroban was less effective than CRTH2 deficiency in all parameters of investigation. One of the possible reasons is that ramatroban antagonizes not only CRTH2 but also TP. Since it is not fully elucidated whether signals through TP, especially in mice, are proinflammatory or antiinflammatory in allergic rhinitis, simultaneous blockage with TP may affect changes of the outcomes induced by CRTH2 antagonism.

In conclusion, we developed a novel model of murine allergic rhinitis that mimics pollinosis. Additionally, we found that CRTH2 plays an essential role in the initiation of allergic rhinitis in mice. These results suggest that this murine model will be useful for elucidating the pathophysiology of allergic rhinitis, especially JCP. These observations may provide a basis for developing therapeutic approaches for managing allergic rhinitis, specifically by inhibiting PGD₂-CRTH2 interactions in the nose of individuals with allergic rhinitis.

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Disclosures

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