IMMUNOLOGY ORIGINAL ARTICLE

Histamine H4 receptor agonists have more activities than H4 agonism in antigen-specific human T-cell responses

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doi:10.1111/j.1365-2567.2007.02574.x
Received 10 March 2006; revised 3 January 2007; accepted 3 January 2007.
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Summary

Histamine not only mediates immediate allergic reactions, it also regulates cellular immune responses. H4R is the most recently identified histamine receptor (HR). In the present study, we examined the *in vitro* effect of histamine and H4R agonists on the responses of human T cells to purified protein derivative from *Mycobacterium tuberculosis* (PPD) and to Cry j1, the major allergen of *Cryptomeria japonica* pollen. Dimaprit, clobenpropit and clozapine, which are H4R agonists, dose-dependently blocked both PPD-induced interferon-γ and Cry j1-induced interleukin-5 production by both peripheral blood mononuclear cells (PBMCs) and antigen-specific T-cell lines. However, the addition of thioperamide, an H3R/H4R antagonist, as well as a mixture of *d*-chlropheniramine, famotidine and thioperamide, did not reverse the inhibition. Pretreatment of PBMCs with SQ22536 and 8-bromoadenosine-3′,5′-cyclic monophosphorothioate, Rp-isomer, had varying abilities to reverse the inhibitory effects of H4R agonists, except for clobenpropit. Moreover, the addition of H4R agonists induced annexin-V expression on PBMCs, especially in $CD19^+$ and $CD4^+$ cells. cDNA microarray analysis revealed that, among 16 600 genes tested, increased expression following treatment with clozapine was seen in 0·8% of the genes, whereas decreased expression was seen in 3·0% of the genes. These results suggest that H4R agonists inhibit antigen-specific human T-cell responses, although H4R does not appear to be important for this effect. In addition, the present study indicated that there may be orphan receptors or HR subtypes which can bind dimaprit, clobenpropit and clozapine, and that can exert an inhibitory effect on antigen-specific cellular responses via a cAMP/cAMP-dependent protein kinase-dependent, apoptotic pathway.

Keywords: cytokine; histamine; H4R; human studies; T cell

Introduction

Histamine has numerous physiological effects, including the induction of allergic responses and gastric acid secretion. These effects are mediated by several histamine receptors (HRs). To date, four subtypes (H1R, H2R, H3R and H4R) of HRs have been identified and cloned. All belong to the seven-transmembrane domain G-protein-coupled receptor family, and coupled G proteins and subsequent activated intracellular signals have been characterized.[1] Of these, H4R was most recently identified, and this receptor is expressed at high levels in mast cells and leucocytes.[2,3]

Histamine not only mediates immediate airway hyperresponsiveness, but also regulates cellular immunity by

Abbreviations: Ag, antigen; APC, antigen-presenting cell; DC, dendritic cell; GAPDH, glyceraldehyde 3-phosphate dehydrogenase; HR, histamine receptor; IFN-γ, interferon-γ; IL, interleukin; 4-MH, 4-methylhistamine; α-MH, alpha-methylhistamine; PBMC, peripheral blood mononuclear cell; 2-PEA, 2-pyridylethylamine; PKA, protein kinase A; PPD, purified protein derivative of *Mycobacterium tuberculosis*; PMA, phorbol 12-myristate 13-acetate; RT–PCR, reverse transcription–polymerase chain reaction; SD, standard deviation; TCC, T-cell clone; TCL, T-cell line; Th1, T helper 1; Th2, T helper 2.

controlling the production of pro-inflammatory cytokines and chemokines, the expression of adhesion molecules, and the migration of inflammatory cells, such as eosinophils.[1,4,5] The maturation and activity of dendritic cells (DCs) is also affected by histamine.[6] In addition, histamine regulates T-cell function.[7,8] For example, histamine can enhance T helper 1 (Th1)-type responses by stimulating H1R, whereas both Th1- and T helper 2 (Th2)-type responses are negatively regulated by H2R.[7] At present, there is one report that $CD8^+$ T cells produce interleukin (IL)-16 in response to histamine activation of H4R.[9] However, despite the high expression of H4R on both antigen-presenting cells and T cells, it is not known whether signals through H4R affect antigen-specific human T-cell responses.[3] Therefore, in the present study, we investigated the roles of H4R agonists in antigen-specific human T-cell responses. The findings presented here may help to identify new therapeutic approaches for using HR agonists to treat allergic diseases.

Materials and methods

Antigen and reagents

The purified protein derivative of *Mycobacterium tuberculosis* (PPD) was purchased from Nihon BCG Seizo Co. (Tokyo, Japan). Cry j1 was purified from the crude extracts of *Cryptomeria japonica* pollen using a well-established procedure.[10] The protein concentration was determined using a bicinchoninic acid assay (Pierce, Rockford, IL), according to the manufacturer's instructions. Endotoxin contamination was considered to be negligible because of a negative Endospec™ ES test result (Seikagaku Kogyo Corporation, Tokyo, Japan). Histamine was purchased from Nacalai Tesque Inc. (Kyoto, Japan). 2-Pyridylethylamine (2-PEA; H1R agonist) and 4-methylhistamine (4-MH; H2R agonist) were provided by GSK (Welwyn, Garden City, UK). Dimaprit (H2R/H4R agonist), clobenpropit (H4R agonist/H3R antagonist) and thioperamide (H3R/H4R antagonist) were purchased from Tocris (Ellisville, MO). Clozapine (H4R agonist) was purchased from MP Biomedicals (Irvine, CA). α-Methylhistamine (α-MH; H3R agonist) was a gift from Professor J. C. Schwartz (INSERM, Paris, France). *d*-Chlropheniramine (H1R antagonist) and famotidine (H2R antagonist) were provided by Yamanouchi Pharmaceutical Co. Ltd. (Tokyo, Japan). SQ22536 was purchased from Sigma (St Louis, MO). RP-8-Br-cAMP was purchased from BIOLOG Life Science Institute (Bremen, Germany).

Isolation and culture of peripheral blood mononuclear cells (PBMCs)

All experiments were approved by the Institutional Review Board in the affiliated hospital of Okayama University Graduate School of Medicine. Informed consent was obtained from each volunteer. Twelve Japanese subjects (five men and seven women; age 20–52 years; mean age 39·5 years) with positive tuberculin skin tests, and 12 Japanese patients (seven men and five women; age 19–59 years; mean age 37·4 years) with Japanese cedar pollinosis showing a positive skin scratch test to Japanese cedar pollen, were examined. PBMCs were isolated and cultured as described previously.[11] The culture medium used throughout the study was RPMI-1640 (Sigma) supplemented with 10% human AB serum (ICN Biomedicals, Aurora, OH), 100 U/ml of penicillin, 100 μg/ml of streptomycin (Sigma) and 20 mM L-glutamine (Gibco BRL, Grand Island, NY). In brief, PBMCs (1×10^6/ml) were incubated in the presence or absence of 2 μg/ml of PPD or 10 μg/ml of Cry j1, together with histamine and/or HR-selective agonists or antagonists, for 72 hr in 24-well plates (Corning Inc., Corning, NY) at 37° in a 5% CO_2/air mixture. To determine the involvement of adenylate cyclase and cAMP-dependent protein kinase A (PKA) in the action of HR agonists, PBMCs were pretreated for 1 hr at 37° with 5 mM SQ22536 and 5 mM RP-8-Br-cAMP, respectively.[12] After this incubation, the cells were washed twice with culture medium and then cultured as described above.

Generation and culture of antigen-specific T-cell lines

The $CD4^+$ PPD^- and Cry j1-specific T-cell lines (TCLs) used were generated using a procedure described previously.[10] In flat-bottomed 96-well microtiter plates (Corning Inc.), 2×10^4 TCL were mixed with 1×10^5 irradiated autologous PBMCs (PBMCx) as antigen-presenting cells (APCs). Following this, the cells were cultured in the presence or absence of antigen (Ag), in 0·2 ml of culture medium, together with HR-selective agonists, for 65 hr.

To determine adenylate cyclase activity, TCLs and/or APCs were incubated with SQ22536 at 37° in 24-well plates for 1 hr. Following this, the cells were washed with culture medium three times, after which they were mixed and cultured in the same manner described above.

Measurement of cytokine production

The levels of interferon-γ (IFN-γ), IL-5 and IL-10 in culture supernatants were measured using Opt EIA™ sets (BD Biosciences, San Jose, CA), according to the manufacturer's instructions. The detection limits for IFN-γ, IL-5 and IL-10 in these assays were 20, 20 and 1·9 pg/ml, respectively.

Analysis of apoptosis by annexin V staining

PBMCs (1×10^6/ml) were incubated with 100 μM histamine or HR-selective agonists for 24 or 72 hr. The cells were then harvested, and apoptotic cells were detected

using an Annexin V-FITC Apoptosis Detection KitI (BD Biosciences), according to the manufacturer's protocol. Stained cells were analysed using a fluorescence-activated cell sorter (FACScan) with CELLQUEST software (BD Biosciences).

cDNA microarray analysis

cDNA microarray analysis was performed using IntelliGene HS Human expression chips, containing about 16 600 probe sets (Takara, Tokyo, Japan). PBMC (1×10^6/ml) were incubated with 2 μg/ml of PPD, in the presence or absence of 100 μM clozapine, for 12 hr. Total cellular RNA was extracted by the RNeasy™ mini kit (Qiagen, Tokyo, Japan), according to the manufacturer's instructions. Four micrograms of total RNA from PBMCs treated with and without clozapine were labeled using the RNA Transcript SureLABEL Core Kit (Takara) with Cy-5 UTP and Cy-3 UTP (Amersham Bioscience Corp., Piscataway, NJ), respectively, in each paired case. Labeled samples were hybridized to IntelliGene HS Human expression chips, according to the manufacturer's instructions. After hybridization for 16 hr at 65°, the slides were washed and then scanned for Cy-5 and Cy-3 fluorescence using the Affymetrix 428 scanner (Affymetrix Japan, Tokyo, Japan). The signal intensity of hybridization was evaluated photometrically by the IMAGENE computer program (BioDiscovery K. K., Tokyo, Japan). A gene expression ratio (Cy-5/Cy-3) of > 2·0 and < 0·5 was considered significant.

Real-time quantitative polymerase chain reaction

PPD- and Cry j1-specific TCLs were immediately soaked in RNAlater™ RNA stabilization reagent (Qiagen) and stored at −30° until use. Total cellular RNA extraction, reverse transcription to generate cDNA, and real-time quantitative polymerase chain reaction (PCR) assays were performed as described previously.[10] In brief, the assays were performed using a GeneAmp 5700 Sequence Detection System (Applied Biosystems, Foster City, CA) with QuantiTect SYBR Green PCR (Qiagen). The PCR primer sequences and product sizes were as follows: H1R, forward 5′-AAGT CACCATCCCAAACCCCCAAG-3′ and reverse 5′-TCAGG CCCTGCTCATCTGTCTTGA-3′ (195 bp); H2R, forward 5′-AGGAACGAGACCAGCAAGGGCAAT-3′ and reverse 5′-GGTGGCTGCCTTCCAGGAGCTAAT-3′ (197 bp); H3R, forward 5′-TGCAAGCTGTGGCTGGTAGTGGAC-3′ and reverse 5′-AGCTCAGGATGGCTGGTCCGTACA-3′ (202 bp); H4R, forward 5′-CCGTTTGGGTGCTGGCCTTCTTAG-3′ and reverse 5′-GATCACGCTTCCACAGGCTCCAAT-3′ (204 bp); and glyceraldehyde 3-phosphate dehydrogenase (GAPDH), forward 5′-ACCACAGTCCATGCCATCAC-3′ and reverse 5′-TCCACCACCCTGTTGCTGTA-3′ (452 bp).[9] The expression level of H1R, H2R, H3R and H4R was estimated by dividing each signal into the signal for GAPDH. As a positive control for H3R, the testicular cell line, NEC14, was used.[13]

Statistical analysis

Statistical comparisons were performed by the non-parametric Mann–Whitney *U*-test and Wilcoxon's signed-rank test. Differences were considered significantly different at a *P*-value of < 0·05. Values are given as means ± standard deviation (SD).

Results

Effect of histamine on PPD-induced IFN-γ production

PBMCs from subjects with positive tuberculin skin tests produced IFN-γ in response to PPD, whereas there was negligible IFN-γ production by PBMCs in the absence of PPD. Histamine inhibited the PPD-induced production of IFN-γ in a dose-dependent manner. Typical results are shown in Fig. 1(a). Using 12 subjects, the mean concentration of IFN-γ induced by PPD was 10 479 ± 10 783 pg/ml. IFN-γ production was significantly inhibited to a mean of 4697 ± 4657 pg/ml (54·3 ± 35·8% inhibition; $P = 0{\cdot}010$ by Wilcoxon's signed-rank test) upon exposure of the cells to 100 μM histamine (Fig. 1b). PBMCs did not produce IL-10 in response to PPD, and the addition of histamine did not alter IL-10 production (data not shown).

Effect of HR-selective agonists on PPD-induced IFN-γ production

Next, we examined the effect of HR-selective agonists on PPD-induced IFN-γ production. H4R agonists, including

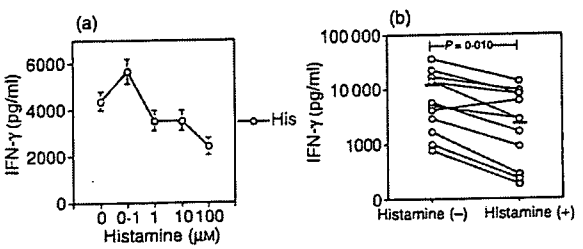

Figure 1. Inhibition of purified protein derivative of *Mycobacterium tuberculosis* (PPD)-induced interferon-γ (IFN-γ) production by histamine. (a) Peripheral blood mononuclear cells (PBMCs) were cultured with 2 μg/ml of PPD in the presence or absence of serial dilutions of histamine. Results are expressed as the mean concentrations ± standard deviation (SD) from triplicate cultures. Data are representative of four separate experiments. (b) PBMCs from 12 subjects with positive tuberculin skin tests were stimulated with 2 μg/ml of PPD in the presence or absence of 100 μM histamine. The *P*-value was obtained using Wilcoxon's signed-rank test. Vertical bars represent the mean concentrations for each group.

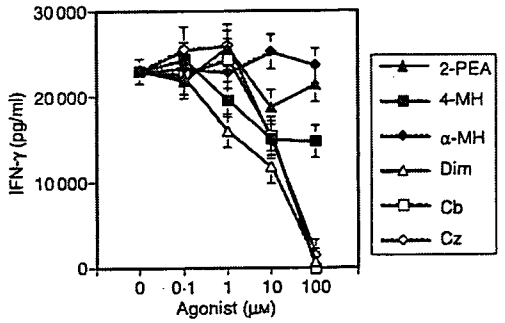

Figure 2. Inhibition of purified protein derivative of *Mycobacterium tuberculosis* (PPD)-induced interferon-γ (IFN-γ) production from peripheral blood mononuclear cells (PBMCs) by histamine receptor (HR)-selective agonists. PBMCs were cultured with 2 μg/ml of PPD in the presence or absence of serial dilutions of HR-selective agonists. Cb, clobenpropit; Cz, clozapine; Dim, dimaprit; 4-MH, 4-methylhistamine; α-MH, alpha-methylhistamine; 2-PEA, 2-pyridylethylamine. Results are expressed as the mean concentrations ± standard deviation (SD) from triplicate cultures. Data are representative of four separate experiments.

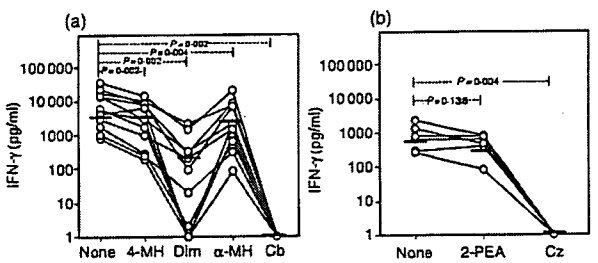

Figure 3. Inhibition of purified protein derivative of *Mycobacterium tuberculosis* (PPD)-induced interferon-γ (IFN-γ) production by histamine receptor (HR)-selective agonists. Peripheral blood mononuclear cells (PBMCs) were stimulated with PPD in the presence or absence of 100 μM HR-selective agonists. (a) Effect of 4-methylhistamine (4-MH), alpha-methylhistamine (α-MH), dimaprit (Dim) and clobenpropit (Cb) on PPD-induced IFN-γ production ($n = 12$). (b) Effect of 2-pyridylethylamine (2-PEA) and clozapine (Cz) on PPD-induced IFN-γ production ($n = 6$). The *P*-values were obtained using Wilcoxon's signed-rank test. Vertical bars represent the mean concentrations for each group.

dimaprit, clobenpropit and clozapine, inhibited PPD-induced IFN-γ production in a dose-dependent manner (Fig. 2). Complete inhibition of PPD-induced IFN-γ production was observed in the presence of 100 μM dimaprit (97·4 ± 3·8% inhibition; $P = 0{\cdot}002$), clobenpropit (100% inhibition; $P = 0{\cdot}002$), or clozapine (100% inhibition; $P = 0{\cdot}004$). In contrast, 100 μM 2-PEA did not cause significant inhibition (33·4 ± 47·2% inhibition; $P = 0{\cdot}138$) of PPD-induced IFN-γ production, and partial inhibition was observed using 100 μM 4-MH (63·6 ± 16·5% inhibition; $P = 0{\cdot}002$) and α-MH (50·3 ± 35·0% inhibition; $P = 0{\cdot}004$) (Fig. 3). None of the HR-related agonists

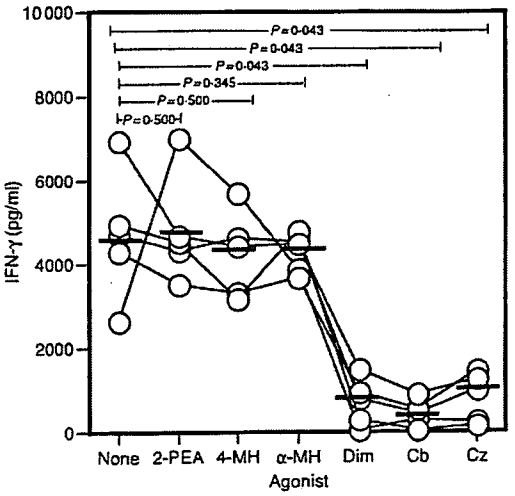

Figure 4. Histamine receptor (HR)-selective agonists-mediated inhibition of purified protein derivative of *Mycobacterium tuberculosis* (PPD)-induced interferon-γ (IFN-γ) production by T-cell lines (TCLs). Five PPD-specific TCLs were mixed with antigen-presenting cells (APCs) and cultured with 2 μg/ml of PPD for 65 hr in the presence of 100 μM 2-pyridylethylamine (2-PEA), 4-methylhistamine (4-MH), alpha-methylhistamine (α-MH), dimaprit (Dim), clobenpropit (Cb) and clozapine (Cz). Following incubation, supernatant was collected and the IFN-γ concentration of each sample was determined by enzyme-linked immunosorbent assay (ELISA). *P*-values were determined using Wilcoxon's signed-rank test. Data on each TCL are representative of two separate experiments.

induced IL-10 production in PPD-stimulated PBMCs (data not shown).

Similar results were seen when we used PPD-specific TCLs, the more purified cell populations. We generated five PPD-specific TCLs from five donors. Treatment with 2-PEA, 4-MH and α-MH did not affect the PPD-specific IFN-γ production. However, treatment with dimaprit, clozapine and clobenpropit strongly and dose-dependently inhibited these responses (Fig. 4).

Effect of HR-selective antagonists on the inhibition of IFN-γ production by H4R-selective agonists

To verify that the H4R-selective agonists inhibit PPD-specific IFN-γ production via H4R, we examined the influence of a panel of HR-specific antagonists. Addition of thioperamide, an antagonist of both H4R and H3R, did not reverse the inhibition of PPD-induced IFN-γ production by either histamine or H4R agonists (Fig. 5a). Furthermore, a mixture of *d*-chlorpheniramine, famotidine and thioperamide did not reverse the inhibition (Fig. 5b). These results were seen in both high responders (IFN-γ production > 10 000 pg/ml) and low responders (IFN-γ production < 10 000 pg/ml) for PPD-induced IFN-γ production (data not shown).

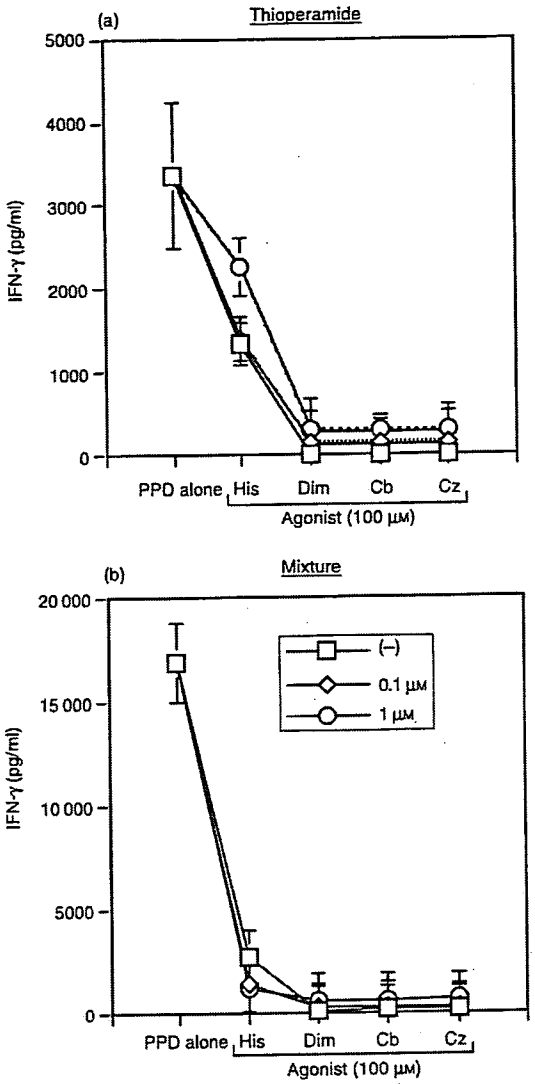

Figure 5. Effect of histamine receptor (HR)-selective antagonists on the inhibition of interferon-γ (IFN-γ) production induced by H4R-selective agonists. Peripheral blood mononuclear cells (PBMCs) were pretreated for 30 min with thioperamide (a) or with a mixture of antagonists (b) at the following concentrations: (a) pretreatment with 0 μM (square), 0·1 μM (diamond) or 1·0 μM (circle) thioperamide; (b) simultaneous pretreatment with each concentration of 0 μM (square), 0·1 μM (diamond) or 1·0 μM (circle) *d*-chlropheniramine, famotidine and thioperamide. Then, cells were incubated with 2 μg/ml of purified protein derivative of *Mycobacterium tuberculosis* (PPD) and 100 μM histamine (His), dimaprit (Dim), clobenpropit (Cb), or clozapine (Cz). Results are presented as the mean concentrations ± standard deviation (SD) from triplicate cultures. Data are representative of three separate experiments.

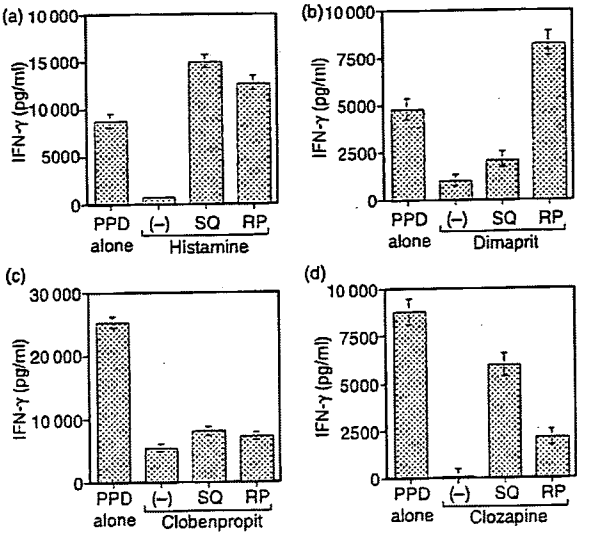

Figure 6. Roles of cAMP and protein kinase A (PKA) in the inhibition of purified protein derivative of *Mycobacterium tuberculosis* (PPD)-induced interferon-γ (IFN-γ) production by H4R-selective agonists. Peripheral blood mononuclear cells (PBMCs) were pretreated for 60 min with SQ22536 (SQ) or RP-8-Br-cAMPS (RP) and then incubated with 2 μg/ml of PPD and 100 μM histamine (a), dimaprit (b), clobenpropit (c), or clozapine (d). The results are expressed as the mean concentrations ± standard deviation (SD) from triplicate cultures. Data are representative of three separate experiments.

Role of adenylate cyclase and apoptosis in histamine suppression of PPD-induced IFN-γ production

We examined whether the inhibition by histamine and H4R-selective agonists depends on the activity of adenylate cyclase. Pretreatment of PBMCs with SQ22536, an adenylate cyclase inhibitor, reversed the inhibition of PPD-induced IFN-γ production by histamine and dimaprit. Furthermore, pretreatment with RP-8-Br-cAMPS, a PKA type 1 inhibitor, completely reversed the inhibition by histamine and dimaprit (Fig. 6a,b). Pretreatment of PBMC with SQ22536 and RP-8-Br-cAMPS also reversed the inhibition by clozapine (Fig. 6d), but the effects were weaker than observed for the reversal of inhibition by histamine. However, a minimal effect of SQ22536 and RP-8-Br-cAMPS was seen on the effect of clopenpropit (Fig. 6c). These results were seen in both high and low responders for PPD-induced IFN-γ production (data not shown). The addition of SQ22536 or RP-8-Br-cAMPS had no effect on the IFN-γ production by PBMCs in response to PPD alone (data not shown).

Pretreatment of PPD-specific TCLs alone with SQ22536, followed by coculture with intact APCs, partially suppressed inhibition of the PPD-specific IFN-γ production by dimaprit. Similar suppression was observed when APCs alone were pretreated with SQ22536, followed by the coculture with intact TCLs. However, pretreatment of both TCLs and APCs with SQ22536 markedly reversed the inhibitory effects of dimaprit on the PPD-specific response (Fig. 7).

The addition of 100 μM dimaprit, clobenpropit, or clozapine, but not of histamine, induced annexin-V expression on PBMCs (Fig. 8). $CD19^+$ cells were highly

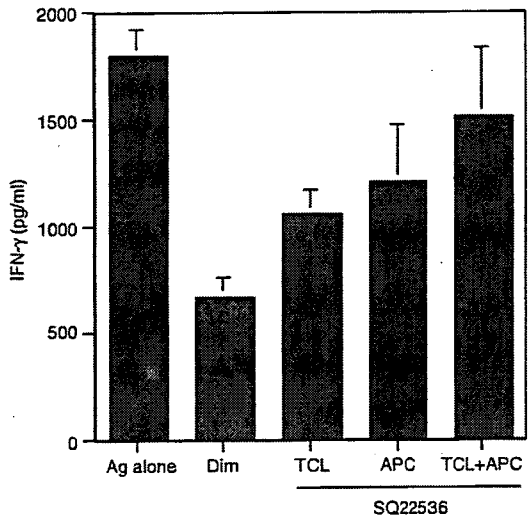

Figure 7. Reversal of H4R-selective agonist-induced inhibition of antigen (Ag)-specific T-cell responses with an adenylate cyclase inhibitor. Purified protein derivative of a *Mycobacterium tuberculosis* (PPD)-specific T-cell line (TCL) alone, antigen-presenting cells (APCs) alone, or both TCL and APC, were pretreated with SQ22536 at 37° for 1 hr. Following incubation, the cells were washed with culture medium three times, after which they were mixed and cultured with the PPD, in the presence of 100 μM dimaprit (Dim), for 65 hr. Data are representative of two separate experiments.

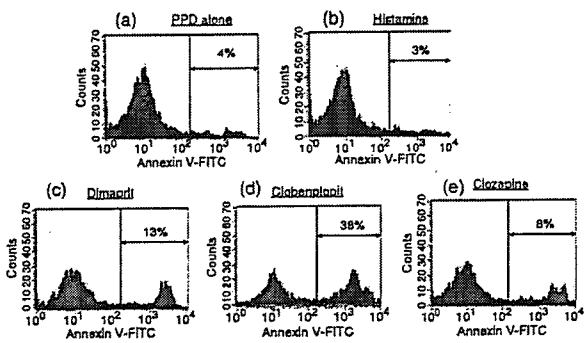

Figure 8. Expression of annexin-V by peripheral blood mononuclear cells (PBMCs) following treatment with H4R-selective agonists. PBMCs were incubated for 72 hr with purified protein derivative of *Mycobacterium tuberculosis* (PPD) (a) and histamine (b), dimaprit (c), clobenpropit (d), or clozapine (e), and the expression of annexin-V on $CD19^+$ cells was analysed by flow cytometry. Data are representative of six separate experiments.

susceptible to the induction of annexin-V expression following exposure to H4R-related agonists. H4R agonists also induced annexin-V expression in $CD4^+$ cells, but not in $CD8^+$ cells (data not shown).

cDNA miroarray analysis

We sought to compare the comprehensive expression of mRNA in PBMC following PPD stimulation in the presence or absence of clozapine. Among 16 600 genes tested, the amounts of mRNA were unchanged in 96·2% of the genes. However, the mRNA levels of 0·8% of the genes (such as melanocortin 1 receptor) were increased (> 200%) in the presence of clozapine. On the contrary, the mRNA levels of 3·0% of the genes, such as IFN-γ, were decreased (< 50%) (Table 1).

Effect of HR-selective agonists on Cry j1-induced IL-5 production

We examined the effect of HR-selective agonists on human Th2 responses. PBMCs from patients with Japanese cedar pollinosis produced a comparable amount of IL-5 in response to Cry j1. The addition of 100 μM 2-PEA, 4-MH or α-MH displayed no significant effect on Cry j1-induced IL-5 production. However, H4R agonists, including dimaprit, clobenpropit and clozapine, significantly inhibited Cry j1-induced IL-5 production (Fig. 9).

Expression of the four histamine receptors on Ag-specific TCLs

Finally, mRNA expression of the four histamine receptors was examined in five PPD- and five Cry j1-specific TCLs by reverse transcription–polymerase chain reaction (RT–PCR). H3R mRNA expression was completely undetectable in all TCLs. On the other hand, H1R, H2R and H4R mRNA were clearly detected in most TCLs (Fig. 10). Using real-time PCR analysis, relative expression levels of the four HRs were not observed to differ significantly among Cry j1- and PPD-specific TCLs (H1R, $P = 0{\cdot}117$; H2R, $P = 0{\cdot}245$; H4R, $P = 0{\cdot}344$; using the Mann–Whitney *U*-test). The expression levels of H4R in TCLs were lower than that of H1R; however, significantly increased expression of the H4R was observed as compared to H2R and H3R (Fig. 11).

Discussion

In the present study, we demonstrated that histamine inhibits PPD-induced IFN-γ production in PBMCs. Several studies have investigated the regulatory role of histamine on IFN-γ production by T cells.[7,8,14–16] Lagier *et al.* reported that histamine inhibits IFN-γ production by human Th1-like T-cell clones (TCCs) specific for *Dermatophagoides pteronyssinus*, whereas it did not have a significant inhibitory effect on T helper 0 (Th0)-like TCCs, and it had no effect on Th2-like TCCs stimulated with phorbol 12-myristate 13-acetate (PMA) and a calcium ionophore.[8] Krouwels *et al.* reported that histamine inhibited IFN-γ production in 21 out of 52 human TCCs (40%), whereas IFN-γ production was enhanced in eight of the TCCs (16%). Also, histamine did not affect IFN-γ production in 23 TCCs (44%) in response to plate-bound

Table 1. Ranked list of up-regulated and down-regulated transcripts in purified protein derivative of *Mycobacterium tuberculosis* (PPD)-stimulated peripheral blood mononuclear cells with clozapine

	Up-regulated transcripts				Down-regulated transcripts		
Rank	Gene name	GenBank acc. no.	Ratio[1]	Rank	Gene name	GenBank acc. no.	Ratio[1]
1	Melanocortin 1 receptor	NM_002386	8·50	1	Interferon-γ	NM_000619	0·02
2	LOC90271	XM_030445	5·59	2	Chemokine (C-C motif) ligand 5	NM_002981	0·02
3	ATP-binding cassette, subfamily G (WHITE) member 1, transcript variant 1	NM_004915	4·75	3	Matrix metalloproteinase 10	NM_002425	0·02
4	Actin-binding LIM protein 2	NM_032432	4·69	4	Chemokine (C-X-C motif) ligand 5	NM_002994	0·03
5	Liver-expressed antimicrobial peptide 2	NM_052971	4·32	5	KIAA1046 protein	NM_014928	0·03
6	Oviductal glycoprotein 1, 120 000 MW	NM_002557	4·30	6	Secreted phosphoprotein 1	NM_000582	0·03
7	Killer-specific secretory protein of 37 000 MW	NM_031950	3·96	7	Chemokine (C-X-C motif) ligand 1	NM_001511	0·03
8	LOC286006	XM_209854	3·83	8	Tumor necrosis factor (ligand) superfamily member 15	NM_005118	0·03
9	Myelin-basic protein	NM_002385	3·73	9	Similar to immune-responsive protein 1	XM_292184	0·04
10	Hypothetical protein LOC157562	XM_098779	3·71	10	Matrix metalloproteinase 7	NM_002423	0·04

[1]Ratio: with clozapine versus without clozapine.
GenBank acc. no., GenBank accession number; MW, molecular weight.

anti-CD3 mAb.[14] In contrast, pretreatment with histamine does enhance IFN-γ production in response to plate-bound anti-CD3 mAb in human Th1 cells.[7] Furthermore, Osna *et al.* showed that the effect of histamine on IFN-γ production was dependent on the stimulatory signals.[15]

We investigated the PPD-induced human T-cell responses to clarify whether histamine affects antigen-specific T-cell responses. Our results are consistent with previous reports. Osna *et al.* reported that histamine up-regulates IL-10 production in murine splenocytes and inhibits IFN-γ production.[16] In the current study, PBMCs did not produce IL-10 in response to PPD, and IL-10 production was not induced in the presence of histamine, suggesting that factors other than IL-10 may be involved in the inhibitory effect of histamine.

The H4R agonists dimaprit, clobenpropit and clozapine all eliminated PPD-induced proliferation and IFN-γ production in PBMCs. H4R is selectively expressed in cells of haematopoietic lineage, including mast cells, eosinophils and lymphocytes.[3,17] Physiological roles of H4R in mast cells, eosinophils, neutrophils and dendritic cells have been implied in recent years, but whether signals through H4R can affect T-cell functions has not been determined.[6,17–19] One report demonstrated that histamine induces IL-16 production by human $CD8^+$ T cells through H2R and H4R.[9] Our results, using HR-related agonists, suggest that signals through H4R may exert an inhibitory role on antigen-specific T-cell responses. However, thioperamide, an H3R and H4R antagonist, did not reverse the inhibition of PPD-induced IFN-γ production by either histamine or H4R agonists. Thioperamide, *d*-chlorpheniramine and famotidine, the HR antagonists used in the present study, were confirmed to be functional in previous studies.[20,21] This suggests that the inhibitory effect of histamine and H4R agonists is not mediated by H4R. In addition, a mixture of *d*-chlorpheniramine, famotidine and thioperamide did not reverse the inhibition by histamine, suggesting that the effect is independent of H1R, H2R and H3R/H4R.

2-PEA, an H1R-selective agonist, did not affect PPD-induced IFN-γ production. On the other hand, 4-MH, an H2R-selective agonist, partially inhibited its production. It is known that histamine regulates cytokine production, via H2R, on T cells.[8,14,15,22] In addition, histamine inhibits IL-12 production by monocytes via H2R.[23] Our finding that dimaprit, an H2R and H4R agonist, inhibited PPD-induced IFN-γ production, suggests that signals through H2R may be involved in the inhibition. However, the inhibitory effect of either histamine or dimaprit

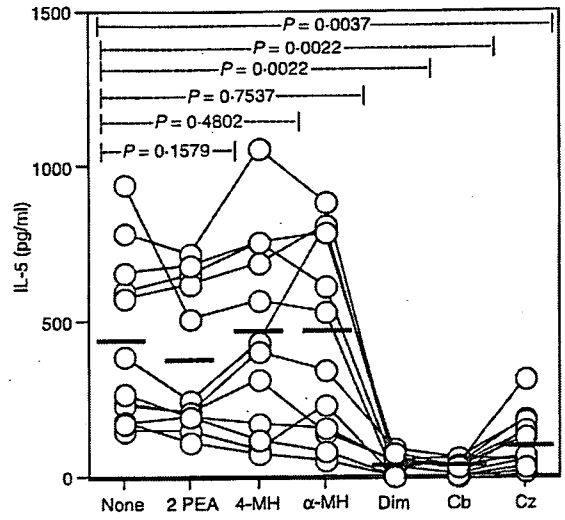

Figure 9. Histamine receptor (HR)-selective agonists-mediated inhibition of Cry j1-specific interleukin (IL)-5 production by peripheral blood mononuclear cells (PBMCs). PBMCs from 12 patients with Japanese cedar pollinosis were cultured with 10 μg/ml of Cry j1, in the presence or absence of 2-pyridylethylamine (2-PEA), 4-methylhistamine (4-MH), alpha-methylhistamine (α-MH), dimaprit (Dim), clobenpropit (Cb) or clozapine (Cz), at 100 μM, for 72 hr. Following incubation, supernatant was collected and the concentrations of IL-5 were determined in each sample using an enzyme-linked immunosorbent assay (ELISA). *P*-values were obtained using Wilcoxon's signed-rank test.

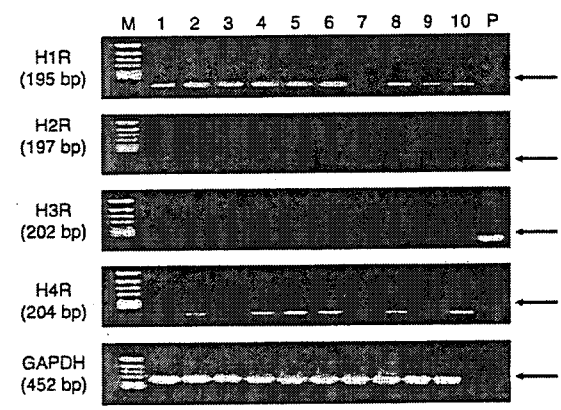

Figure 10. Expression of four histamine receptors (HRs) by human T-cell lines (TCLs). mRNA was extracted from five Cry j1-specific TCLs (lanes 1–5) and from five purified protein derivative of *Mycobacterium tuberculosis* (PPD)-specific TCLs (lanes 6–10), after which the levels of H1R, H2R, H3R, H4R and glyceraldehyde 3-phosphate dehydrogenase (GAPDH) were detected by reverse transcription–polymerase chain reaction (RT–PCR), as described in the Materials and methods. M, molecular marker; P, positive control (NEC14).

was not reversed by famotidine, suggesting that H2R signalling had a negligible role in the inhibition of PPD-induced IFN-γ production.

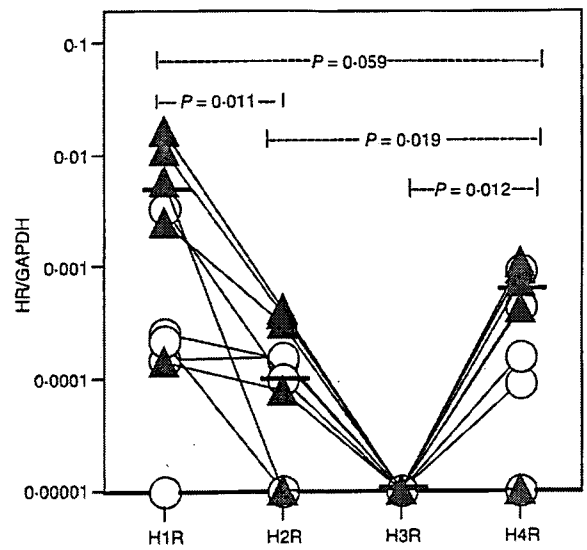

Figure 11. Comparison of the amounts of four histamine receptors (HRs) among T-cell lines (TCLs). The expression levels of four HRs were determined in five Cry j1-specific TCLs (closed triangle) and in five purified protein derivative of *Mycobacterium tuberculosis* (PPD)-specific TCLs (open circle) using real-time reverse transcription–polymerase chain reaction (RT–PCR). Each bar represents the median expression level of each messenger. *P*-values were obtained using Wilcoxon's signed-rank test.

The pretreatment of PBMCs with SQ22536, an adenylate cyclase inhibitor, and with RP-8-Br-cAMPS, a PKA type 1 inhibitor, reversed the inhibition of PPD-induced IFN-γ production by histamine and H4R agonists. Previous reports demonstrated that 5 mM SQ22536 and 5 mM RP-8-Br-cAMPS reversed, almost completely, the inhibitory effect of several compounds on human PBMC responses.[12] These results suggest that H4R agonists, except for clobenpropit, inhibit PPD-induced IFN-γ production by elevating intracellular cAMP levels and activating PKA. Moreover, results using PPD-specific TCLs and APCs suggest that H4R agonists may influence PPD-specific cellular responses at both the T-cell and APC level. It is known that H2R activation causes an elevation of the intracellular cAMP level.[24] In addition, PKA plays a pivotal role in histamine-mediated regulation of IFN-γ production, especially via the stimulation of T-cell receptors.[15] Although dimaprit can act as an H2R agonist, clozapine and clobenpropit cannot.[25] H4R is coupled to $G_{i/o}$, which leads to the inhibition of cAMP formation.[26] This further supports the possibility that the inhibitory effect of H4R agonists is not associated with typical H4R signaling. Rather, signals similar to those mediated by H2R may participate in the inhibition. However, we also observed that the inhibitory effect of either histamine or dimaprit was not reversed by famotidine, suggesting that H2R signaling had a negligible role in the inhibition of PPD-induced IFN-γ production. In addition, the varied effect of SQ22536 and RP-8-Br-cAMPS on IFN-γ

production induced by different agonists may suggest the presence of unidentified pleural receptors in the action of agonists.

$CD19^+$ and $CD4^+$ cells express annexin-V following exposure to H4R agonists, suggesting that these compounds induce apoptosis in these cells. On the other hand, cDNA microarray analysis revealed that the changes of mRNA levels were seen in 0·8% of the genes tested, such as melanocortin 1 receptor, following the stimulation with H4R agonist (Table 1), indicating that the inhibitory effects of H4R agonists were not non-specific or solely the result of an apoptotic effect. For example, melanocortin 1 receptor has signal transducer activity and it is involved in immunosuppression.[27] Thus, the suppressive role of H4R agonists may be associated with the activation of melanocortin 1 receptor. In addition, histamine did not induce the expression of annexin-V. These results suggest that the inhibitory effect of H4R agonists is not associated with the binding to classical HRs.

Concentrations of histamine and H4R agonists ranging from 10^{-5} to 10^{-4} M displayed a dose-dependent inhibition of PPD-induced IFN-γ production by PBMCs. Although it was difficult to define precisely the histamine concentration in the target organ, concentrations of histamine from 10^{-6} to 10^{-4} M have been reported to be comparable to those measured in tissues after mast cell degranulation.[28]

In conclusion, we examined the effect of histamine and H4R agonists on antigen-specific human T-cell responses. H4R signaling is important for functions of other immune cells, such as mast cell chemotaxis, eosinophil chemotaxis and suppression of IL-12 production by dendritic cells.[3,29] H4R agonists inhibit Ag-specific cytokine production; however, our investigations, using antagonists of H4R and inhibitors of adenylate cyclase or PKA, revealed that H4R plays a negligible role in the inhibition. These results indicate that there may be a previously unidentified HR or receptor subtype that can bind to dimaprit, clobenpropit and clozapine and that can mediate the inhibition of antigen-induced cellular responses via a cAMP/PKA-dependent, apoptotic pathway. More recently, Lim *et al.* have reclassified 4-MH as the most selective H4R agonist so far at the H4R.[30] This seems to be relevant for understanding the present results, suggesting a new orphan receptor. Furthermore, our observations may provide the basis for novel therapeutic approaches in the management of allergic and autoimmune diseases.

Acknowledgements

The authors would like to thank Yuko Okano for her editorial assistance. This work was supported, in part, by grants from Research on Allergic disease and Immunology of Ministry of Health, Labor and Welfare (no. 14210301 to MO).

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Biosci. Biotechnol. Biochem., 72, 70572-1–7, 2008

Glycoform Analysis of Japanese Cypress Pollen Allergen, Cha o 1: A Comparison of the Glycoforms of Cedar and Cypress Pollen Allergens

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Received September 5, 2007; Accepted October 18, 2007; Online Publication, February 7, 2008
[doi:10.1271/bbb.70572]

A Japanese cypress (*Chamaecyparis obtusa*) pollen allergen, Cha o 1, is one of the major allergens that cause allergic pollinosis in Japan. Although it has been found that Cha o 1 is glycosylated and that the amino acid sequence is highly homologous with that of Japanese cedar pollen allergen, the structure of *N*-glycans linked to Cha o 1 remains to be determined. In this study, therefore, we analyzed the structures of the *N*-glycans of Cha o1. The *N*-glycans were liberated by hydrazinolysis from purified Cha o 1, and the resulting sugar chains were *N*-acetylated and pyridylaminated. The structures of pyridylaminated *N*-glycans were analyzed by a combination of exoglycosidase digestion, two dimensional (2D-) sugar chain mapping, and electrospray ionization mass spectrometry analysis. Structural analysis indicated that the major *N*-glycan structure of Cha o1 is GlcNAc2Man3Xyl1Fuc1GlcNAc2 (89%), and that high-mannose type structures (Man9-GlcNAc2, Man7GlcNAc2) occur as minor components (11%).

Key words: *N*-glycan structure; antigenic oligosaccharide; Japanese cypress pollen allergen; Cha o 1; *Chamaecyparis obtusa*

In previous studies,[1,2] we determined the chemical structures of *N*-glycans linked to two cedar pollen allergens, Cry j 1 (Japanese cedar pollen allergen) and Jun a 1 (mountain cedar pollen allergen), and revealed that biantennary plant complex type *N*-glycans harboring Lewis a epitope occur in their *N*-glycan moieties. This finding suggests that the Lewis a epitope may play a critical role in pollinosis, but the occurrence of this epitope in plant glycoallergens has been reported from only three pollen allergens, Cup a 1 (pollen allergen from Arizona cypress),[3] Cry j 1, and Jun a 1. Japanese cypress pollen is another major allergic pollen in Japan, and Cha o 1 is a major allergen contained in the cypress pollens. Although it is known that Cha o 1 is *N*-glycosylated,[4] the detailed chemical structures of the *N*-glycan moiety remain to be determined. Hence, in this study, we analyzed the structures of *N*-glycans linked to the Japanese cypress pollen allergen Cha o 1 to determine whether plant specific antigenic oligosaccharide or Lewis a epitope occurs in the allergen. First, we purified Cha o 1 from an extract of the cypress pollens by a combination of ion-exchange chromatography and gel-filtration, using an antiserum against Cha o 1 to monitor the elution position of the allergen. We found that Cha o 1 occured in two forms, with the same N-terminal amino acid sequence but different molecular weights, suggesting that the numbers of the *N*-glycosylation sites might be different from each other. Furthermore, structural analysis of *N*-glycans revealed

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Abbreviations: PA-, pyridylamino; RP-HPLC, reverse-phase HPLC; SF-HPLC, size-fractionation HPLC; ESI-MS, electrospray ionization mass spectrometry; CBB, Coomassie Brilliant Blue; Hex, hexose; HexNAc, *N*-acetylhexosamine; Deoxyhex, deoxyhexose; Pen, pentose; M3FX, Manα1-6(Manα1-3)(Xylβ1-2)Manβ1-4GlcNAcβ1-4(Fucα1-3)GlcNAc-PA; MFX, Xylβ1-2Manβ1-4GlcNAcβ1-4(Fucα1-3)GlcNAc-PA; GN2M3FX, GlcNAcβ1-2Manα1-6(GlcNAcβ1-2Manα1-3)(Xylβ1-2)Manβ1-4GlcNAcβ1-4(Fucα1-3)GlcNAc-PA; M9A, Manα1-2Manα1-6(Manα1-2Manα1-3)-Manα1-6(Manα1-2Manα1-2Manα1-3)Manβ1-4GlcNAcβ1-4GlcNAc-PA; M7A, Manα1-2Manα1-6(Manα1-3)Manα1-6(Manα1-2Manα1-3)Manβ1-4GlcNAcβ1-4GlcNAc-PA

that Cha o 1 bears both a biantennary complex type and a high-mannose type oligosaccharide. The predominant occurrence of the antigenic plant complex type structure, GlcNAc2Man3Xyl1Fuc1GlcNAc2 (GN2M3FX), is a characteristic common to allergenic pollen glycoproteins.[1-3] But the Lewis a unit was not found in the *N*-glycans of Cha o 1, in contrast with Cup a 1, Cry j 1, and Jun a 1, indicating that the Lewis a epitope is not involved in the symptoms of pollinosis.

Materials and Methods

Materials. An Asahipak NH2P-50 4E column (0.46 × 25 cm) was purchased from Showa Denko (Tokyo, Japan), and a Cosmosil 5C18-AR column (0.6 × 25 cm) from Nacalai Tesque (Kyoto, Japan). GN2M3FX were prepared from glycoproteins from rice culture cells.[5] M7A and M9A were prepared from royal jelly glycoproteins.[6] Antiserum against Cha o 1 was a generous gift of Meiji Co. Antiserum against β1-2 xylose-containing *N*-glycans was a generous gift of Dr. Arnd Strum (Friedrich-Miescher Institute, Basel, Switzerland).[7]

Purification of Cha o 1. Purification of Cha o 1 was basically done as described in a previous paper.[4] During the purification steps, the elution of Cha o 1 was monitored by immunoblotting assay using antiserum against Cha o 1. Japanese cypress pollen (100 g) was defatted in acetone (500 ml), and the resulting defatted pollen was suspended in 125 mM $(NH_4)_2CO_3$ and sonicated in an ice bath for 5 min. After incubation for 16 h at 4 °C, the extract was centrifuged at 8,000 rpm for 20 min, and the resulting supernatant was 80% saturated with ammonium sulfate. The protein precipitate was dissolved in a small amount of 10 mM Tris–HCl buffer, pH 7.8, and dialyzed against the same buffer (5-liter) for 2 d. After centrifugation, the resulting supernatant (total $OD_{280\,nm}$, $A_{280\,nm}$ × sample volume = 717.60) was applied to a DEAE cellulose column (4 × 40 cm) equilibrated with 10 mM Tris–HCl buffer, pH 7.8. The run-through fraction was pooled and dialyzed against 10-liter (5-liter × 2 times) of 10 mM Na-acetate buffer, pH 5.0, containing 0.1 M NaCl for 2 d. The dialyzate was applied to a SP-Toyopearl (3 × 22 cm) column equilibrated with the same buffer. After the column was washed with the same buffer (about 600 ml), bound proteins were eluted by 10 mM Na-acetate buffer, pH 5.0, containing 0.5 M NaCl. The bound fraction (the Cha o 1 fraction) was dialyzed against 10-liter (5-liter × 2 times) of 10 mM Na-acetate buffer, pH 5.0, containing 0.1 M NaCl for 2 d, and the resulting dialysate (total $OD_{280\,nm}$ = 29.68) was applied to the SP-Toyopearl (3 × 22 cm) column equilibrated with the same buffer. In a second cation-exchange chromatography, the bound proteins were eluted by a linear gradient of NaCl from 0.1 M to 0.5 M in 10 mM Na-acetate buffer, pH 5.0. The Cha o 1 fraction, indicated by a horizontal bar in Fig. 1-A, was pooled and concentrated to about 7 ml by Amicon Centriprep-30. The total $OD_{280\,nm}$ of the concentrated sample was 5.26. Cha o1 was further purified by gel-filtration with a Superdex 200 column (GE-Healthcare, 1.6 × 120 cm) in 25 mM Tris–HCl buffer, pH 7.8, containing 0.1 M NaCl. As shown in Fig. 1-B, Cha o 1 was separated from some other contaminative proteins, but two protein bands (around 47 kDa) were detected on the SDS-gel by CBB staining (Fig. 2-I) and on the PVDF membrane by immunoblotting using the antiserum against Cha o 1 (Fig. 2-II), suggesting that Cha o 1 occurs in several isoforms, as reported by Suzuki *et al.*[4] Furthermore, as shown in Fig. 2-III, the purified Cha o 1 was recognized by the

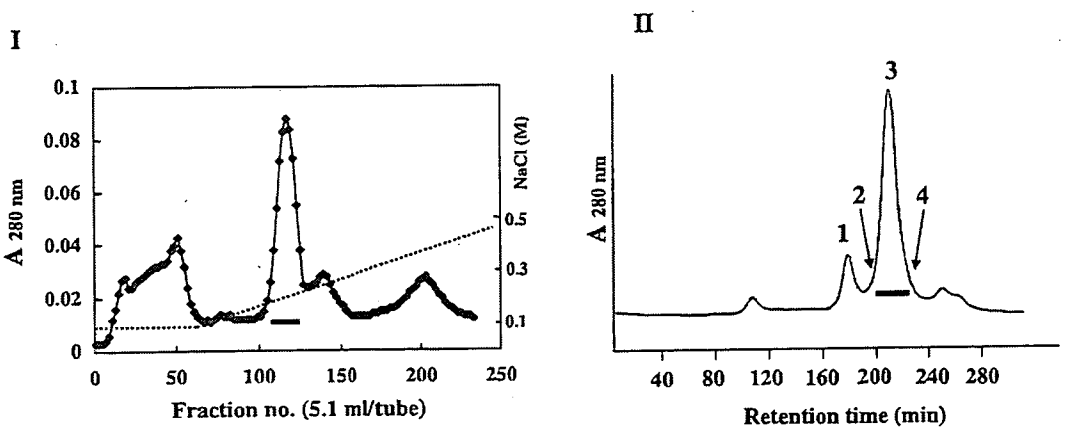

Fig. 1. Purification of Cha o 1.

I, SP-Toyopearl chromatography of partially purified Cha o1. Partially purified Cha o 1 was loaded on a SP-Toyopearl column in 10 mM Na-acetate buffer, pH 5.0. The allergen was eluted by a linear gradient of NaCl from 0.1 M to 0.5 M in 10 mM Na-acetate buffer, pH 5.0. The Cha o 1-containing fraction, detected by immunoblotting, was pooled as indicated by a horizontal bar. II, Gel-filtration of the Cha o 1 fraction obtained in I. The concentrated Cha o 1 fraction obtained by SP-Toyopearl chromatography was loaded on a Superdex 200 column (1.6 × 120 cm). The column was developed with 25 mM Tris–HCl buffer, pH 7.8, containing 0.1 M NaCl at a flow rate of 0.8 ml/min.

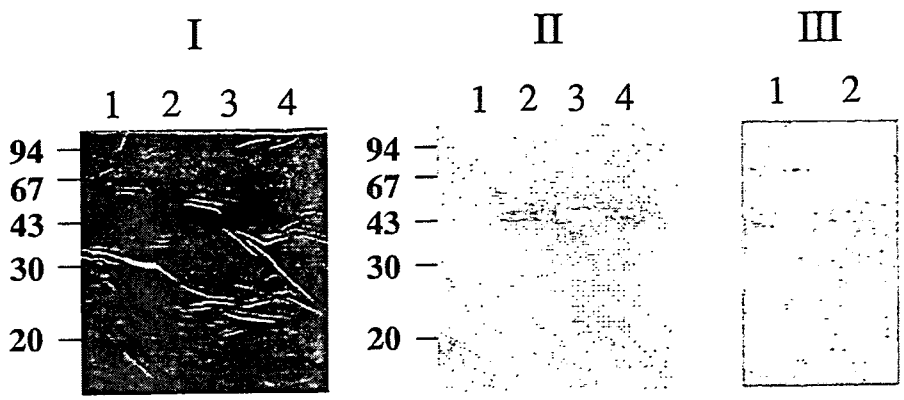

Fig. 2. SDS–PAGE and Immunoblotting.
I, CBB staining of 20% polyacrylaminde gel. Lane 1, peak 1 in Fig. 1-II; lane 2, position 2 in Fig. 1-II; lane 3, peak 3 in Fig. 1-II; lane 4, position 4 in Fig. 1-II. II, Immunoblotting using anti-Cha o 1 antibody. Lane 1, peak 1 in Fig. 1-II; lane 2, position 2 in Fig. 1-II; lane 3, peak 3 in Fig. 1-II; lane 4, position 4 in Fig. 1-II. III, Immunoblotting using anti-β1-2xylose antibody. Lane 1, peak 1 in Fig. 1-II; lane 2, peak 3 in Fig. 1-II. Each immunoblot was done as described in previous papers.[4,8]

anti-β1-2 xylose antibody,[7,8] indicating that Cha o 1 bears plant-complex type *N*-glycans. After two protein bands were cut on PVDF membrane separately, each N-terminal amino acid sequence was analyzed, and it was found that the two proteins had the same N-terminal sequence (D-N-P-I-D-), indicating that they were Cha o 1. Based on these results, we used the Cha o 1 fraction, indicated by a horizontal bar in Fig. 1-II, in glycoform analysis without further purification.

Preparation of pyridylaminated N-glycans from Cha o 1. *N*-Glycans were released by hydrazinolysis (100 °C, 12 h, in 200 µl of anhydrous hydrazine) from the lyophilized Cha o 1 (2.6 mg). After *N*-acetylation of the hydrazinolysate with saturated ammonium bicarbonate (400 µl) and acetic anhydride (20 µl), the acetylated hydrazinolysate was desalted using Dowex 50 × 2 resins. Pyridylamination of the sugar chains was done by the method of Natsuka and Hase.[9] Separation of PA-sugar chains was done by HPLC on a Jasco 880-PU HPLC apparatus with a Jasco 821-FP Intelligent Spectrofluorometer, using the Shodex Asahipak NH2P-50 column (0.46 × 25 cm) and the Cosmosil 5C18-AR column (0.6 × 25 cm). On the Cosmosil 5C18-AR column, the PA-sugar chains were eluted by increasing the acetonitrile concentration in 0.05% TFA linearly from 0 to 10% at a flow rate 1.2 ml/min. In the case of size-fractionation HPLC using the Asahipak NH2P-50 column, the PA-sugar chains were eluted by increasing the water content in the water-acetonitrile mixture from 36% to 62% linearly for 60 min at a flow rate of 0.7 ml/min.

Electrospray ionization (ESI) mass spectrometry. ESI-MS analysis of PA-sugar chains was done as described in our previous reports,[5,6] using a Perkin Elmer Sciex API-III triple-quadrupole mass spectrometer with an atmospheric-pressure ionization ion source.

Glycosidase digestion of PA-sugar chains. Digestion with jack bean α-mannosidase, diplococcal β-*N*-acetylglucosaminidase, and *Aspergillus* α-1,2-mannosidase was done using about 200 pmol of the PA-sugar chains under the conditions described in our previous reports.[5,10] The resulting glycosidase-digests were analyzed by SF-HPLC using the Asahipak NH2P-50 column (0.46 × 25 cm).

Results and Discussion

Purification of PA-sugar chains

First, the PA-sugar chains from Cha o 1 were partially purified by RP-HPLC, as shown in Fig. 3. Three peaks

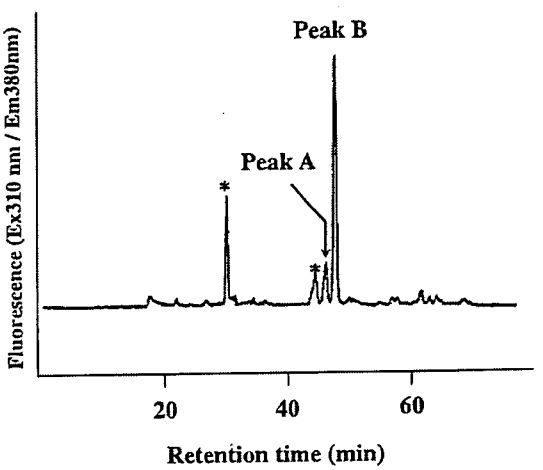

Fig. 3. RP-HPLC Profiles of PA-Sugar Chains from Cha o 1.
Peak A and peak B were confirmed to be relevant N-glycans by ESI-MS, and were used for structural analysis. PA-derivatives were loaded on the Cosmosil 5C 18-AR column (6.0 × 250 mm) equilibrated with 0.05% TFA. The PA-sugar chains were eluted by an increase in acetonitrile concentration. Star mark (*) shows contaminative peaks.

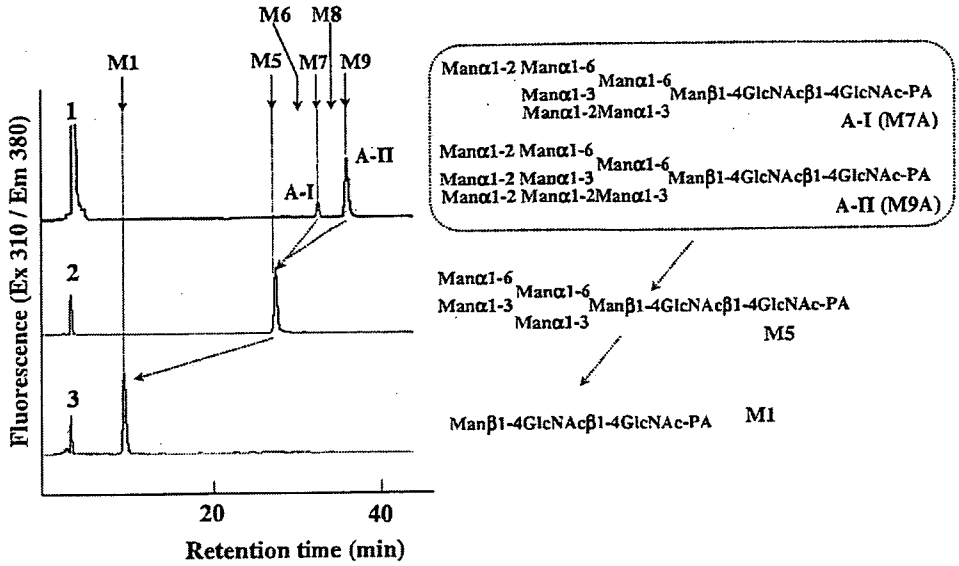

Fig. 4. SF-HPLC of Exoglycosidase Digests of Peak A.
1, PA-sugar chains in peak A in Fig. 3; 2, the *Aspergillus* α-1,2-mannosidase digest of 1; 3, the jack bean α-mannosidase digest of 2. Arrows (M1, M5, M6, M7, M8, and M9) indicate the elution positions of authentic PA-sugar chains: Man1GlcNAc2-PA, Man5GlcNAc2-PA, Man6GlcNAc2-PA, Man7GlcNAc2-PA, Man8GlcNAc2-PA, and Man9GlcNAc2-PA.

were observed in the region where *N*-glycans are expected to be eluted (40–70 min), but it was determined by exoglycosidase digestion that peaks A and B were relevant pyridylaminated *N*-glycans. A small peak eluted just before peak A was not digested by some exoglycosidases, suggesting that this peak might not be *N*-glycan, although MS/MS analysis of it to confirm the presence of GlcNAc-PA (*m/z* 300) could not be done due to the small amount of the sample.

Structures of PA-sugar chains peak A

When peak A in Fig. 3 was analyzed by SF-HPLC, two PA-sugar chains were detected, as shown in Fig. 4-1. The elution positions of these two PA-sugar chains corresponded to those of authentic PA-sugar chains: A-I to Man7GlcNAc2 and A-II to Man9-GlcNAc2-PA. Furthermore, the elution positions of A-I and A-II on RP-HPLC corresponded to those of M7A and M9A respectively. When these PA-sugar chains were treated with *Aspergillus* α-1,2-mannosidase, a new product was eluted at the elution position of M5A (Man5GlcNAc2-PA), suggesting that A-I and A-II contained two and four α1-2 mannose residues respectively (Fig. 4-2). The product was further converted to M1 (Man1GlcNAc2-PA) by jack bean α-mannosidase, as shown in Fig 4-3.

From these results, the structures of A-I and A-II were proposed to be M7A and M9A, respectively, as shown in Fig. 4.

Structural analysis of N-glycans in peak B

As shown in Fig. 5-I, only one PA-sugar chain was detected in peak B in Fig. 3. The elution position corresponded to that of GN2M3FX. The elution position of this PA-sugar chain on RP-HPLC also corresponded to that of GN2M3FX (data not shown), suggesting that the structure of this *N*-glycan is the biantennary plant complex type structure, GlcNAc2Man3Xyl1Fuc1GlcNAc2. ESI-MS analysis of peak B showed a single signal at *m/z* 1674.5 $[(M+H)^+]$ (Fig. 5-II), suggesting that this PA-sugar chain consisted of (HexNAc)3(Hex)3(Deoxyhex)1(Pen)1(HexNAc-PA) or GlcNAc2-Man3Xyl1Fuc1GlcNAc2-PA. The deduced structure was further confirmed by exoglycosidase digestion. This PA-sugar chain was converted to M3FX with diplococcal β-*N*-acetylglucosaminidase, suggesting that two GlcNAc residues were bound by a β1-2 linkage (Fig. 5-I-2). The product was further converted to MFX by jack bean α-mannosidase digestion (Fig. 5-I-3). The data of 2-D sugar chain mapping, exoglycosidase digestion, and ESI-MS analysis suggested that the structure of peak B was GN2M3FX, as shown in Fig. 5.

Comparison of *structural feature of N-glycans linked to cedar pollen allergen (Jun a 1 and Cry j 1) and cypress pollen allergen (Cha o 1)*

As shown in Table 1, we have found that the cedar pollen allergens (Jun a 1 and Cry j 1) carry plant-complex type *N*-glycans containing the Lewis a antigen (Galβ1-3(Fucα1-4)GlcNAcβ1-) unit.[1,2] In addition to these two cedar pollen allergens, it has been reported that Arizona cypress pollen allergen, Cup a 1, also bears the Lewis a unit in the *N*-glycan moiety.[3] Although the physiological function of the Lewis a unit in plant *N*-glycans is still obscure, there is a possibility that the antigenic unit is involved in the symptoms of pollinosis.

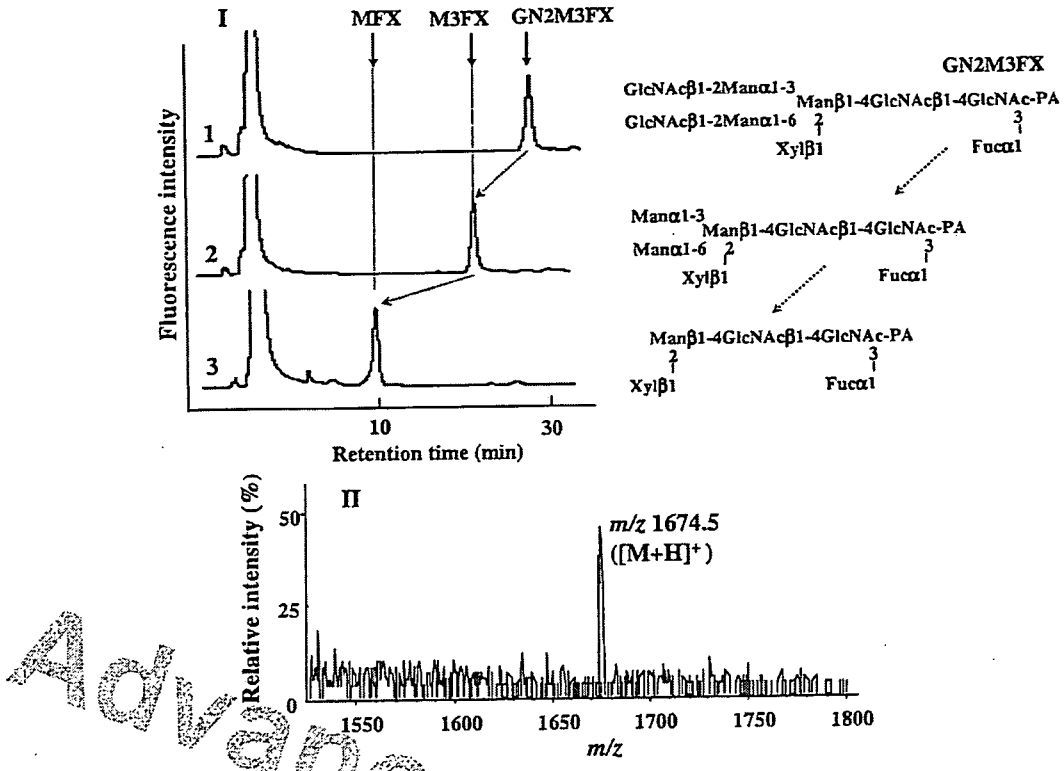

Fig. 5. SF-HPLC of Exoglycosidase Digests of Peak B and ESI-MS Spectrum.

I, SF-HPLC of exoglycosidase digests of peak B. 1, PA-Sugar chain in peak B in Fig. 3; 2, the diplococcal β-GlcNAc-ase digest of I; 3, the jack bean α-mannosidase digest of 2. II, ESI-MS spectrum of Peak B. The PA-sugar chain was observed as a single charged ion, $[M+H]^+$.

Table 1. Comparison of *N*-Glycan Structures of Two Cedar Pollen Allergens (Jun a 1, Cry j 1) and Cha o 1

Structures of *N*-Glycans	Jun a 1-A[a]	Jun a 1-B[a]	Cry j 1[b]	Cha o 1
GlcNAcβ1-2 {Manα1-6, Manα1-3} Manβ1-4GlcNAcβ1-4GlcNAc (2: Xyl β1; 3: Fuc α1)	ND	3%	ND	ND
GlcNAcβ1-2Man α1-6, GlcNAcβ1-2Man α1-3 Manβ1-4GlcNAcβ1-4GlcNAc (2: Xyl β1; 3: Fuc α1; Fucα1 on 4)	75%	76%	47%	89%
Galβ1-3GlcNAcβ1-2 Man α1-6, Man α1-3 Man β1-4GlcNAc β1-4GlcNAc (2: Xyl β1; 3: Fuc α1; Fucα1 on 4)	23%	21%	38%	ND
Galβ1-3GlcNAcβ1-2 Man α1-6, Galβ1-3GlcNAcβ1-2 Man α1-3 Man β1-4GlcNAc β1-4GlcNAc (2: Xyl β1; 3: Fuc α1; Fucα1 on 4)	2%	ND	15%	ND
Manα1-2Manα1-6, Manα1-2Manα1-3 Manα1-6, Manα1-2Manα1-2Manα1-3 Manβ1-4GlcNAcβ1-4GlcNAc	ND	ND	ND	9%
Manα1-2Manα1-6, Manα1-3 Manα1-6, Manα1-2Manα1-3 Manβ1-4GlcNAcβ1-4GlcNAc	ND	ND	ND	2%

a, reference 1; b, reference 2

Hence, in this study, we analyzed the glycoform of *N*-glycans of Japanese cypress pollen allergen, Cha o 1, one of the major pollen glycoallergens in Japan. Molecular cloning of Cha o 1 revealed that this Japanese cypress pollen allergen is highly homologous with the two cedar pollen allergens (Cry j 1 and Jun a 1), and that there are six Asn-X-Thr/Ser sequences.[4] Although two (Asn(259)-Pro-Thr(261) and Asn(272)-Asp-Thr(274)) of them might not be glycosylated, it is not known whether the remaining four *N*-glycosylation sites are actually glycosylated. As described in a previous report,[4] Cha o 1 was purified in two isoforms with the same *N*-terminal amino acid sequence (D-N-D-I-P) but different molecular weights (Fig. 2-I), and these two isoforms were recognized by the antiserum against plant complex type *N*-glycans (Fig. 2-III). The difference in molecular weight of the two Cha o 1 molecules might reflect the difference in the numbers of actually glycosylated sites in the four *N*-glycosylation consensus sequences.

Structural analysis of *N*-glycans revealed that the complex type *N*-glycan harboring the Lewis a epitope did not occur in Cha o 1 and that major structure was the biantenary plant complex type structure: GlcNAc-β1-2Manα1-6(GlcNAcβ1-2Manα1-3)(Xylβ1-2)Manβ1-4GlcNAcβ1-4 (Fucα1-3)GlcNAc (GN2M3FX) (Fig. 5 and Table 1). This result suggest that the Lewis a epitope in the *N*-glycan moiety is not involved in the symptoms of pollinosis. It is noteworthy, however, that a high content of the GM2M3FX structure is a common feature of the *N*-glycans of allergenic pollen glycoproteins (Jun a 1, Cry j 1, Cup a 1, olive pollen allergen Ole e1, *Ginkgo biloba* pollen glycoprotein, and palm pollen glycoprotein).[1–3,11–13] Comparing the cedar pollen allergens (Jun a 1 and Cry j 1) and Arizona cypress pollen allergens (Cup a 1), the occurrence of high-mannose type *N*-glycans appears to be specific to Japanese cypress pollen allergen (Cha o 1), although the content is very low. Among plant glycoallergens, it has been reported that a peanut allergen, Ara h 1, carries the high-mannose type *N*-glycans (Man6-5GlcNAc2) in addition to xylosylated *N*-glycans.[11] And recently it has been proposed that the *N*-glycan of Ara h 1 is a ligand of dendritic cell-specific ICAM-grabbing nonintegrin (DC-SIGN) and that it acts as a Th2 ajuvant.[14] Since DC-SIGN is a C-type lectin specific to mannose residues in glycans, it is possible to assume that the *N*-glycans linked to Cha o 1 are ligands of DC-SIGN, and that Cha o 1 can prime Th2-skewed T-cell responses. Detail analysis of the immunological activity of the *N*-glycans of Cha o1 to dendritic cells is necessary to determine the involvement of plant *N*-glycans in the symptoms of pollinosis.

Acknowledgments

This work was supported in part by grants from the Ministry of Education, Culture, Sports, Science, and Technology of Japan (Basic Research (C), no. 17580300) and the Okayama University COE program, Establishment of Plant Health Science. The authors are grateful to the ESI-MS Laboratory of Okayama University.

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The Journal of Immunology

CRTH2 Plays an Essential Role in the Pathophysiology of Cry AQ:A,B j 1-Induced Pollinosis in Mice[1]

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PGD_2 is the major prostanoid produced during the acute phase of allergic reactions. Two PGD_2 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 PGD_2–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, 179: 0000–0000.

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](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 administration of pollen extracts in the absence of adjuvants is needed.

Prostanoids are thought to participate in allergic inflammation (10). PGD_2 is one of the most important of these and it plays roles in allergic respiratory diseases including allergic rhinitis (10–15). For example, nebulized PGD_2 enhances Th2-type inflammatory responses and eosinophilia, leading to the development of airway hyperresponsiveness (14). PGD_2 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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Received for publication July 23, 2007. Accepted for publication February 8, 2008.

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[1] This work was supported in part by grants from the Ministry of Education, Culture, Sports, Science, and Technology, Japan (14704143), and Research on Allergic Disease and Immunology of the Ministry of Health, Labor, and Welfare, Japan (14210301).

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

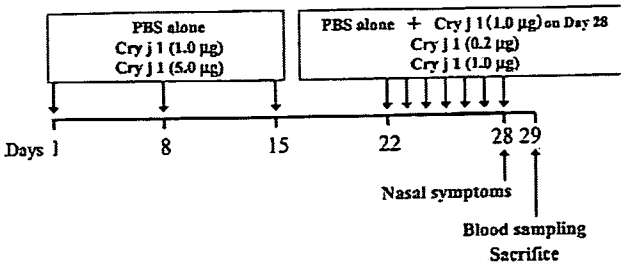

FIGURE 1. Experimental design used to investigate the effect of nasal exposure to Cry j 1 in mice. BALB/c mice (6–9 per group) were sensitized by intranasal administration of either 1.0 or 5.0 μg of Cry j 1 in 10 μl PBS in the absence of adjuvants once a week for 3 wk (on days 1, 8, and 15). AQ: H One week after the third sensitization, mice were challenged by intranasal administration of 0.2 or 1.0 μg of Cry j 1, respectively every day for 7 AQ: I 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 pathophysiologies 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 AQ: C 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 F1 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 nodules 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% CO_2 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% H_2O_2, 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 T1 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	TCAGCTGTGTCTGGGCCACT	TTATGAGTAGGGACAGGAAGCCTCA	133	NM_010558
IL-13	TGCTTGCCTTGGTGGTCTC	CAGGTCCACACTCCATACC	151	NM_008355
IFN-γ	GCGTCATTGAATCACACCTG	ACCTGTGGGTTGTTGACCTC	103	NM_008337
IL-1β	TCCAGGATGAGGACATGAGCAC	GAACGTCACACCAGCAGGTTA	105	NM_008361
IL-6	CCACTTCACAAGTCGGAGGCTTA	GCAAGTGCATCATCGTTGTTCATAC	112	NM_031168
TNF-α	ATGAGCACAGAAAGCATGATC	TCCACTTGGTGGTTTGCTACG	305	NM_013693
RANTES	AGATCTCTGCAGCTGCCCTCA	GGAGCACTTGCTGCTGGTGTAG	170	NM_013653
Eotaxin	CAGATGCACCCTGAAAGCCATA	TGCTTTGTGGCATCCTGGAC	96	NM_011330
CRTH2	TCTCAACCAATCAGCACACC	CCTCCAAGAGTGGACAGAGC	173	NM_009962
GAPDH	ACCACAGTCCATGCCATCAC	TCCACCACCCTGTTGCTGTA	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 ± 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, F2 respectively (Fig. 2*A*). 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. 2*B*).

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. 2*C*). There was also a significant elevation in the concentration of Cry j 1-specific IgG1 (Fig. 2*D*). 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. 2*E*).

Eosinophil infiltration into nasal mucosa, another characteristic of pollinosis, is rarely seen in the nasal mucosa in control mice (Fig. 3*A*). On the contrary, there was a marked accumulation of F3 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. 3*D*). 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

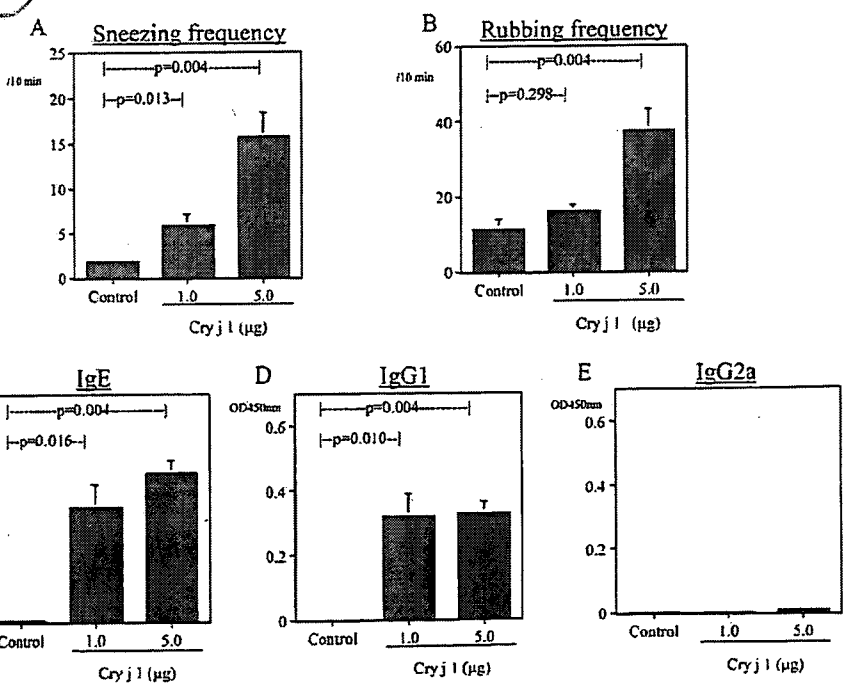

FIGURE 2. Nasal hyperresponsive symptoms and Ab production in mice following intranasal sensitization and challenge with Cry j 1. Mice were sensitized and challenged by intranasal administration of Cry j 1. Nasal allergic symptoms, including the frequency of sneezing (*A*) and rubbing (*B*), were determined for the 10 min immediately following the final nasal challenge (day 28). Mean frequencies ± 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 ± SEM are shown. Results are representative of two independent experiments.