

Prostaglandin D₂-induced eosinophilic airway inflammation is mediated by CRTH2 receptor

Yoshiki Shiraishi^{*§}, Koichiro Asano^{*§}, Takeshi Nakajima^{*§}, Tsuyoshi
Oguma^{*}, Yusuke Suzuki^{*}, Tetsuya Shiomi^{*}, Koichi Sayama^{*}, Kyoko
Niimi^{*§}, Misa Wakaki^{*§}, Junko Kagyo^{*§}, Eiji Ikeda[†], Hiroyuki Hirai[¶],
Kazuhiro Yamaguchi^{*§}, and Akitoshi Ishizaka^{*§}

^{*}Division of Pulmonary Medicine, Department of Medicine (Y.S., K.A.,
T.N., T.O., Y.S., T.S., K.S., K.N., M.W., J.K., K.Y., A.I.), [†]Department of
Pathology (E.I.), [§]Pfizer-Keio Research Laboratories, Shinanomachi
Research Park (Y.S., K.A., T.N., K.N., M.W., J.K., K.Y., A.I.), Keio
University School of Medicine, Tokyo, Japan

[¶]R&D Center, BML Laboratories (H.H.), Saitama, Japan

Running Title

PGD₂-induced airway eosinophilia and CRTH2 receptor

Address correspondence to:

Koichiro Asano, M. D.

Division of Pulmonary Medicine

Department of Medicine

Keio University School of Medicine

35 Shinanomachi, Shinjuku-ku, Tokyo 160-8582, Japan

Phone: +81-3-3353-1211

FAX: +81-3-3353-2502

E-mail: ko-asano@qa2.so-net.ne.jp

Number of Text Pages	12 pages
Number of Tables	0 tables
Number of Figures	7 figures
Number of References	28 references
Number of words in Abstract	219 words
Number of words in Introduction	454 words
Number of words in Discussion	918 words

Abbreviations: PGD₂, prostaglandin D₂; IL-5, interleukin-5; DK-PGD₂, 13,14-dihydro-15-keto-PGD₂; MK-PGD₂, 11-deoxy-11-methylene-15-keto-PGD₂; BAL, bronchoalveolar lavage; TP, thromboxane A₂ receptor; BW 245C, [5-(6-carboxyhexyl)-1-(3-cyclohexyl-3-hydroxypropyl)-hydantoin; I-BOP, [1S-1 α ,2 β (5Z),3 α (1E,3R*),4 α)]-7-[3-(3-hydroxy-4-(4'-iodophenoxy)-1-butenyl)-7-oxa bicyclo-[2.2.1]heptan-2-yl]-5-heptenoic acid; BW A868C, 3-benzyl-5-(6-carboxyhexyl)-1-(2-cyclohexyl-2-hydroxyethylamino)-hydantoin;

SQ29,548, 5-heptenoic,
7-[3-[[2-[(phenylamino)carbonyl]hydrazino]methyl]-7-oxabicyclo[2.2.1]hept-2-yl]-[1S-
[1alpha ,2alpha (Z),3alpha ,4alpha]]

Abstract

Mast cell-derived prostaglandin D₂ (PGD₂) is one of the essential modulators of eosinophilic airway inflammation in asthma and allergic rhinitis. Two G protein-coupled receptors for PGD₂, DP and CRTH2, are both expressed on the surface of eosinophils, and CRTH2 has been demonstrated to mediate PGD₂-induced eosinophil mobilization *in vitro*. However, it has not yet been determined whether PGD₂ and its receptors mediate *in vivo* eosinophil trafficking into the airways or other organs. We demonstrated that intratracheal administration of PGD₂ in rats pretreated with systemic interleukin-5 (IL-5) injection induced marked airway eosinophilia, determined by the differential counts of cells in bronchoalveolar lavage (BAL) fluid and lung histology, within 2 hours. Systemic IL-5 alone significantly increased the number of eosinophils in the peripheral blood, but showed no effect on airway eosinophilia. Three CRTH2-specific agonists (DK-PGD₂, MK-PGD₂, and indomethacin) demonstrated equivalent induction of BAL eosinophilia to that of PGD₂, but a DP agonist (BW 245C) or a TP agonist (I-BOP) showed no effect. PGD₂- or CRTH2 agonist-induced BAL eosinophilia was almost completely inhibited by pretreatment with a CRTH2/TP antagonist, ramatroban (BAY u-3405), while a TP-specific antagonist, SQ29,548, or a DP-specific antagonist, BW A868C, did not inhibit the effects of PGD₂. These results suggest that CRTH2 plays a significant role in the eosinophil trafficking from the bloodstream into the airways in PGD₂-related airway inflammation.

Introduction

Lipid mediators such as prostaglandins, leukotrienes, and platelet activating factor are essential modulators of allergic airway inflammation in asthma and allergic rhinitis. Several recent studies demonstrated that prostaglandin D₂ (PGD₂), which is the major cyclooxygenase metabolite released from activated mast cells, is also essential for the pathogenesis of eosinophilic airway inflammation (O'sullivan et al., 1998; Bochenek et al., 2004). PGD₂ is released during the early and late asthmatic responses following allergen exposure in patients with asthma (O'sullivan et al., 1998; Bochenek et al., 2004), and has been demonstrated to be a potent chemoattractant for eosinophils *in vitro* (Hirai et al., 2001; Monneret et al., 2001) and *in vivo* (Emery et al., 1989; Woodward et al., 1990). We previously reported that cyclooxygenase-2 inhibitors, which abolished PGD₂ synthesis in the lungs of allergen-sensitized and exposed guinea pigs, attenuated eosinophil accumulation in the airways (Oguma et al., 2002). Other researchers reported that overexpression of PGD₂ synthase or inhalation of aerosolized PGD₂ enhanced eosinophilic and lymphocytic airway inflammation in mice following allergen exposure (Fujitani et al., 2002; Honda et al., 2003).

The bioactivity of PGD₂ is mediated by two G protein-coupled receptors, DP and CRTH2, both of which are expressed on the surface of eosinophils (Gervais et al., 2001). DP receptor expression in the lungs is upregulated in allergic inflammation in mice (Matsuoka et al., 2000; Fujitani et al., 2002), and disruption of the DP gene abolished the accumulation of eosinophils and lymphocytes in a murine model of asthma (Matsuoka et al., 2000). DP receptor antagonists, such as S-5751 and BW A868C, also reduced the number of eosinophils in allergen-induced upper and lower airway inflammation in guinea pigs (Arimura et al., 2001). However, a DP-specific agonist,

BW 245C, did not replicate the effects of PGD₂ on eosinophil mobilization *in vitro* (Hirai et al., 2001; Monneret et al., 2001) and *in vivo* (Woodward et al., 1990), suggesting that PGD₂-induced eosinophil chemotaxis is mediated by a receptor other than DP.

A second PGD₂ receptor, CRTH2, which has been identified as a molecule preferentially expressed on Th2 lymphocytes, eosinophils, and basophils, has been demonstrated to transduce direct chemotactic or chemokinetic activity of PGD₂ for eosinophils (Nagata et al., 1999a; Nagata et al., 1999b; Hirai et al., 2001; Monneret et al., 2001). A CRTH2-specific agonist, 13,14-dihydro-15-keto-PGD₂ (DK-PGD₂), enhances eosinophil migration and activation as potently as PGD₂ *in vitro* (Gervais et al., 2001; Hirai et al., 2001; Monneret et al., 2001). Therefore, it is likely that CRTH2, at least partially, mediates PGD₂-dependent eosinophil migration to inflammatory sites. However, there is no evidence suggesting that CRTH2-mediated signals are important *in vivo* for the accumulation of eosinophils in local organs such as the airways. We thus examined the role of the CRTH2 receptor in PGD₂-induced airway eosinophilic inflammation.

Materials and Methods

Animals

Specific pathogen-free, male Brown Norway rats, weighing 230-250 g, were purchased from Charles River Japan (Yokohama, Japan). All rats were housed at the facility in Biobubble Barrier Units under positive pressure.

Either rat interleukin-5 (IL-5, 0.2 ng/kg, R&D Systems, Minneapolis, MN) or PBS was injected intravenously one hour prior to administration of prostanoid receptor agonists. The agonists, including PGD₂, two CRTH2-specific agonists, DK-PGD₂ and 11-deoxy-11-methylene-15-keto-PGD₂ (MK-PGD₂), a DP-specific agonist, BW 245C, and a thromboxane A₂ receptor (TP)-specific agonist, I-BOP, were purchased from Cayman Chemical Co. (Ann Arbor, MI), and indomethacin was purchased from Nacalai Tesque Inc. (Kyoto, Japan). Each reagent was dissolved at a concentration of 0.01 - 1 mM in 100 μl PBS (pH 7.4) containing ethanol (PGD₂, BW 245C, I-BOP, indomethacin) or methylacetate (DK-PGD₂, MK-PGD₂). Since the eosinophil count in bronchoalveolar lavage fluid was equivalent regardless of the type of vehicle (PBS alone; $0.14 \pm 0.11 \times 10^4$ cells/ml, n = 3, PBS with ethanol; $0.27 \pm 0.11 \times 10^4$ cells/ml, n = 3, PBS with methylacetate; $0.47 \pm 0.05 \times 10^4$ cells/ml, n = 4), the combined data from all vehicle-treated rats were used in the analysis. Tracheostomy was performed under anesthetization with intraperitoneal ketamine (100 mg/kg) and xylazine (10 mg/kg), and the agonists or vehicles were sprayed intratracheally using a MicroSprayer™ Aerosolizer (model IA-1C with FMJ-250 high pressure syringe; Penn-Century, Philadelphia, PA). After the neck incision was sutured, the rats were allowed to awaken and were then returned to the cages.

In some experiments, a CRTH2/TP antagonist, ramatroban [BAY-u3405,

(+)-(3R)-3-(4-fluorobenzenesulfonamido)-1,2,3,4-tetra-hydrocarbazole-9-propionic acid, 3 - 10 mg/kg in 0.5% methyl cellulose, p.o.], a DP antagonist, BW A868C (1 mg/kg in normal saline containing ethanol, i.v., Cayman Chemical Co.), or a TP antagonist, SQ29,548 (2.5 mg/kg in normal saline containing ethanol, i.v., Cayman Chemical Co.) was administered two hours prior to administration of agonists. A previous study demonstrated that 1 - 10 mg/kg ramatroban administered orally in male rats resulted in the peak plasma concentration of 0.16 - 4.6 mg/L (385 - 11,000 nM) (Boberg et al., 1997), which is far above the concentration of ramatroban to block PGD₂-binding to rat CRTH2 *in vitro* (IC₅₀; 45 nM) (Shichijo et al., 2003).

The experimental protocol was reviewed and approved by the Laboratory Animal Care and Use Committee of Keio University School of Medicine.

Bronchoalveolar lavage (BAL)

The rats were sacrificed by injection of an overdose of pentobarbital at 2, 8, and 24 hours after the agonists were administered. The trachea was cannulated and the lungs were lavaged three times with 8 ml PBS (pH 7.4).

Total cells in BAL fluid were counted using a hemocytometer, and the cell types were determined on Diff-Quik-stained cytospin slides prepared with Auto Smear CF12D (Sakura Finetech, Tokyo, Japan). Four hundred cells in duplicate slides were counted in a blinded fashion.

Histological examination

After BAL was performed, the chest was opened, and the pulmonary circulation was thoroughly flushed with PBS using a peristaltic pump (flow rate 5 ml/min) through a

catheter inserted in the pulmonary artery. The lungs were removed and fixed in 4% (w/v) neutralized buffered paraformaldehyde (pH 7.4) at 4°C. Lung tissues were paraffin-embedded, and the sliced sections were stained with Giemsa stain. A semi-quantitative scoring system was used to grade the degree of eosinophil accumulation. Each bronchus or vessel was graded from 0 (no eosinophils) to 4 (abundant eosinophilic infiltration) in a blinded manner. Five bronchi and vessels were evaluated in each side of the lungs, and the lung score (0 - 4) represents the mean value of the scores of both lungs. The lungs were examined independently by three investigators, and the scores were averaged.

Peripheral blood cell count

In an independent experiment, the rats received intravenous injection of IL-5 (0.2 ng/kg) or PBS one hour prior to intratracheal administration of PGD₂ (100 nmoles/animal) or vehicle. A peripheral blood sample was collected every hour after administration of IL-5 to determine the kinetics of blood eosinophils. The blood sample (10 µl), 50%(w/v) phloxine B solution (40 µl), and 0.05% methylene blue solution (50 µl) were mixed gently for 15 minutes, and the number of total leukocytes and eosinophils was determined.

Statistical analysis

All values are expressed as mean and SEM. Comparisons were performed by one-way ANOVA followed by Bonferroni/Dunn procedure as a post hoc test. A *p*-value less than 0.05 was considered statistically significant (STATVIEW 1992-98, SAS Institute Inc., NC).

Results

Intratracheal administration of PGD₂ (100 nmoles/animal) following IL-5 pretreatment (0.2 ng/kg, i.v.) induced a marked increase in the number of eosinophils in BAL fluid, whereas treatment with either PGD₂ alone or IL-5 alone showed no effect on BAL eosinophilia (Figure 1). In order to determine whether the eosinophilia in BAL fluid merely reflects the number of peripheral blood eosinophils, we examined the kinetics of eosinophils in the peripheral blood. Intravenous administration of IL-5 induced a 3-4 fold increase in the number of eosinophils in the peripheral blood within 2 hours ($p < 0.05$, Figure 2). PGD₂, however, did not demonstrate any additive or synergistic effects with IL-5 on blood eosinophilia (Figure 2), indicating that PGD₂ is essential for the local eosinophil trafficking from peripheral blood to the airway. The number of eosinophils in BAL fluid was dependent on the dose of PGD₂ (1 - 100 nmoles /animal, $p < 0.01 - 0.05$, Figure 3A). Eosinophilia in BAL fluid was observed within 2 hours after administration of PGD₂, and the number of eosinophils had decreased to the baseline at 8 and 24 hours (Figure 3B).

The biological activities of PGD₂ are mediated through multiple eicosanoid receptors on the cell surface, including CRTH2, DP, and TP (Hamid-Bloomfield et al., 1990; Boie et al., 1995; Hirai et al., 2001; Gervais et al., 2001; Monneret et al., 2001). We thus examined the specific receptor essential for PGD₂-induced eosinophil accumulation in the lungs. Two PGD₂-derivatives specific for CRTH2 (DK-PGD₂, MK-PGD₂), at a dose of 100 nmoles/animal, demonstrated an equivalent effect on eosinophil accumulation in BAL fluid to that of 100 nmoles/animal PGD₂ (Figure 4). Furthermore, indomethacin, which has a significantly different structure from PGD₂ or

its derivatives but exhibits similar agonistic activity for CRTH2 (Hirai et al., 2002), also showed potent eosinophil chemotactic activity *in vivo* (Figure 4). In contrast, a DP agonist, BW 245C (100 nmoles/animal), or a TP agonist, I-BOP (100 nmoles/animal), demonstrated little effect on eosinophil accumulation in BAL fluid (Figure 4). PGD₂-induced BAL eosinophilia was significantly inhibited by pretreatment with a CRTH2/TP antagonist, ramatroban, in a dose-dependent manner (3 – 10 mg/kg, $p < 0.05$ – 0.01, Figure 5A). Ramatroban (10 mg/kg) also inhibited the accumulation of eosinophils induced by CRTH2 agonists (DK-PGD₂, MK-PGD₂, indomethacin, $p < 0.01$, Figure 5B). In contrast, a TP-specific antagonist, SQ29,548, or a DP antagonist, BW A868C, did not inhibit the effects of PGD₂ on BAL eosinophilia (Figure 5A).

Histological examination demonstrated that intratracheal administration of PGD₂ in rats pretreated with IL-5 resulted in significant eosinophil accumulation in the perivascular and peribronchial spaces ($p < 0.01$, Figures 6, 7). Neither IL-5 nor PGD₂ alone could induce accumulation of eosinophils around bronchi or blood vessels. Treatment with ramatroban (10 mg/kg) almost completely abolished PGD₂-induced eosinophil accumulation in the lungs (data not shown).

Discussion

CRTH2, a newly-identified PGD₂ receptor, has been demonstrated to mediate PGD₂-induced mobilization and activation of inflammatory cells such as eosinophils *in vitro* (Gervais et al., 2001; Hirai et al., 2001; Monneret et al., 2001). Recent studies have demonstrated that an intravenous injection of a CRTH2 agonist such as Δ^{12} -PGJ₂ or DK-PGD₂ induced eosinophil recruitment from the bone marrow into the bloodstream (Heinemann et al., 2003; Shichijo et al., 2003). The present study clearly demonstrated that CRTH2 is also essential for PGD₂-induced recruitment of eosinophils from the bloodstream into organs.

Since PGD₂ can activate multiple receptors including CRTH2, DP, and TP (Hamid-Bloomfield et al., 1990; Boie et al., 1995, Hirai et al., 2001; Gervais et al., 2001; Monneret et al., 2001), we used a combination of receptor-specific agonists and antagonists to confirm the role of CRTH2. As CRTH2 agonists, we used DK-PGD₂, a well-established CRTH2-specific agonist *in vitro*, and MK-PGD₂, a stable analog of DK-PGD₂, although their specificity *in vivo* is not known. We thus performed additional experiments using another compound, indomethacin. Indomethacin has a significantly different structure from PGD₂ or its derivatives such as DK-PGD₂ and MK-PGD₂, but has been demonstrated to exhibit potent agonistic activity for CRTH2 (Hirai et al., 2002). All the CRTH2 agonists including indomethacin demonstrated equivalent activity to induce pulmonary eosinophilia to that of PGD₂, while a DP-specific agonist, BW 245C, or a TP-specific agonist, I-BOP, did not have such activity. Furthermore, a CRTH2/TP dual antagonist, ramatroban (3 – 10 mg/kg), abolished the effects of PGD₂ and all the CRTH2-specific agonists on BAL eosinophilia, but neither a DP antagonist, BW A868C, nor a TP antagonist, SQ29,548, did. We thus

concluded that PGD₂ in the airway lumen can attract eosinophils through the activation of CRTH2.

Previous studies demonstrated that an intravenous injection of PGD₂ or a CRTH2 agonist can induce peripheral blood eosinophilia (Heinemann et al., 2003; Shichijo et al., 2003). In the present study, however, intratracheally administered PGD₂, at a dose that induced significant BAL eosinophilia, exhibited no effect on the number of blood eosinophils. The discrepancy is possibly due to the difference in dose of agonists required to induce eosinophilia in peripheral blood and in local organs. Shichijo et al. reported that at least 100 µg DK-PGD₂ per rat (3×10^{-7} mol/rat) was necessary to induce peripheral blood eosinophilia when administered intravenously (Shichijo et al., 2003). In the present study, PGD₂ and CRTH2 agonists administered intratracheally induced significant eosinophilia in BAL at a lower dose of 10^{-9} - 10^{-7} mol/rat.

Intratracheally administered PGD₂ alone could not induce pulmonary eosinophilia as previously reported (Fujitani et al., 2002; Honda et al., 2003). We thus examined the synergistic activity of PGD₂ and systemic IL-5. Such an interaction between eosinophil chemoattractants and IL-5 in eosinophil trafficking to peripheral organs has been thoroughly examined for eotaxin, a well-established eosinophilic CC chemokine. Eotaxin-induced accumulation of eosinophils in the skin or lungs of guinea pigs or mice is amplified by either intravenous administration of IL-5 or overexpression of the IL-5 gene, but is completely abolished in IL-5-deficient mice (Collins et al., 1995; Rothenberg et al., 1996; Mould et al., 1997). Peripheral blood eosinophilia alone induced by adoptive transfer of eosinophils could not mimic the effects of systemic IL-5, suggesting that priming of circulating eosinophils by IL-5 is essential for eotaxin-induced tissue eosinophilia. In contrast, IL-5 has been shown to desensitize

eosinophils to PGD₂ by downregulating the expression of CRTH2 (Hamada et al., 2004). Similar phenomenon has been observed *in vivo*; eosinophils isolated from IL-5 transgenic mice can not bind to PGD₂ (Hirai et al., 2003). Further study is required to determine the interaction of PGD₂ and IL-5 during the induction of pulmonary eosinophilia.

Fukuyama and colleagues (Fukuyama et al., 2000) previously reported that intratracheally-administered human eotaxin induced airway eosinophilia in guinea pigs. The magnitude of airway eosinophilia induced by eotaxin (2 - 200 nmoles/animals) was almost equivalent to that induced by PGD₂ (100 nmoles/animals) in the present study, but more persistent. Increased number of eosinophils in BAL fluid was observed within 6 hours and persisted for 7 days in the eotaxin-injected guinea pigs, while PGD₂-induced airway eosinophilia disappeared within 8 hours in our model. However, sustained PGD₂ release during the early and late phase of allergic inflammation, which has been observed in the airways exposed to an allergen in animal models (Fujitani et al., 2002; Oguma et al., 2002) and in atopic subjects (O'sullivan et al., 1998; Bochenek et al., 2004), may result in prolonged airway eosinophilia. This is supported by the fact that a CRTH2/TP antagonist, ramatroban, effectively suppressed the airway eosinophil accumulation in sensitized guinea pigs even at 24 hours after the final allergen exposure (Nagai et al., 1995). There may be an alternative pathway for PGD₂ to induce eosinophil accumulation in the late phase of allergic inflammation, which was not examined in the present study. In a murine model of asthma, an inhalation of aerosolized PGD₂ induced the expression of macrophage-derived chemokine (MDC, CCL22) through an unidentified PGD₂ receptor on bronchial epithelial cells, and recruited Th2 lymphocytes into the airway (Honda et al., 2003). PGD₂ may then

enhance the production of eosinophilic cytokines such as IL-4, IL-5, and IL-13 from activated Th2 lymphocytes via CRTH2 receptor (Tanaka et al., 2004).

In conclusion, the present study demonstrated that CRTH2 receptor activation by PGD₂ released at the site of inflammation is essential for the pathogenesis of eosinophilic airway inflammation, suggesting that PGD₂ synthase inhibitors or CRTH2 antagonists can be useful to control allergic airway diseases such as asthma and allergic rhinitis.

Acknowledgments

Ramatroban was generously donated by Bayer Yakuhin, Ltd. (Osaka, Japan). We thank Satoshi Kusakari, Hitoshi Abe, Minako Suzuki, Kiyora Nakajima, and Yuko Hashimoto for their excellent technical assistance.

References

Arimura A, Yasui K, Kishino J, Asanuma F, Hasegawa H, Kakudo S, Ohtani M, and Arita H (2001). Prevention of allergic inflammation by a novel prostaglandin receptor antagonist, S-5751. *J Pharmacol Exp Ther* 298: 411-419.

Boberg M, Ahr HJ, Beckermann B, Buhner K, Siefert HM, Steinke W, Wunsche C, and Hirayama M (1997). Pharmacokinetics and metabolism of the new thromboxane A₂ receptor antagonist ramatroban in animals. 1st communication: absorption, concentrations in plasma, metabolism, and excretion after single administration to rats and dogs. *Arzneimittelforschung* 47: 928-938.

Bochenek G, Nizankowska E, Gielicz A, Swierczynska M, and Szczeklik A (2004). Plasma 9 α ,11 β -PGF₂, a PGD₂ metabolite, as a sensitive marker of mast cell activation by allergen in bronchial asthma. *Thorax* 59: 459-464.

Boie Y, Sawyer N, Slipetz DM, Metters KM, and Abramovitz M (1995). Molecular Cloning and Characterization of the Human Prostanoid DP Receptor. *J Biol Chem* 270: 18910-18916.

Collins PD, Marleau S, Griffiths_Johnson DA, Jose PJ, and Williams TJ (1995). Cooperation between interleukin-5 and the chemokine eotaxin to induce eosinophil accumulation in vivo. *J Exp Med* 182: 1169-1174.

Emery DL, Djokic TD, Graf PD, and Nadel JA (1989). Prostaglandin D₂ causes accumulation of eosinophils in the lumen of the dog trachea. *J Appl Physiol* 67: 959-962.

Fujitani Y, Kanaoka Y, Aritake K, Uodome N, Okazaki_Hatake K, and Urade Y (2002). Pronounced eosinophilic lung inflammation and Th2 cytokine release in human lipocalin-type prostaglandin D synthase transgenic mice. *J Immunol* 168: 443-449.

Fukuyama S, Inoue H, Aizawa H, Oike M, Kitamura M, Yoshie O, and Hara N

(2000). Effect of eotaxin and platelet-activating factor on airway inflammation and hyperresponsiveness in guinea pigs in vivo. *Am J Respir Crit Care Med* 161: 1844-1849.

Gervais FG, Cruz RP, Chateauneuf A, Gale S, Sawyer N, Nantel F, Metters KM, and O'Neill GP (2001). Selective modulation of chemokinesis, degranulation, and apoptosis in eosinophils through the PGD₂ receptors CRTH2 and DP. *J Allergy Clin Immunol* 108: 982-988.

Hamada, K, Yamada Y, Kamada Y, Ueki S, Yamaguchi K, Oyamada H, Fujita M, Usami A, Chiba T, Kanda A, Kayaba H, and Chihara J (2004). Prostaglandin D₂ and interleukin-5 reduce CRTH2 surface expression on human eosinophils. *Allergol Int* 53:179-184.

Hamid-Bloomfield S, Payne AN, Petrovic AA, and Whittle BJ (1990). The role of prostanoid TP- and DP-receptors in the bronchoconstrictor effect of inhaled PGD₂ in anaesthetized guinea-pigs: effect of the DP-antagonist BW A868C. *Br J Pharmacol* 100: 761-766.

Heinemann A, Schuligoi R, Sabroe I, Hartnell A, and Peskar BA (2003). Δ^{12} -prostaglandin J₂, a plasma metabolite of prostaglandin D₂, causes eosinophil mobilization from the bone marrow and primes eosinophils for chemotaxis. *J Immunol* 170: 4752-4758.

Hirai H, Tanaka K, Yoshie O, Ogawa K, Kenmotsu K, Takamori Y, Ichimasa M, Sugamura K, Nakamura M, Takano S, and Nagata K (2001). Prostaglandin D₂ selectively induces chemotaxis in T helper type 2 cells, eosinophils, and basophils via seven-transmembrane receptor CRTH2. *J Exp Med* 193: 255-261.

Hirai H, Tanaka K, Takano S, Ichimasa M, Nakamura M, and Nagata K (2002). Agonistic effect of indomethacin on a prostaglandin D₂ receptor, CRTH2. *J Immunol* 168: 981-985.

Hirai H, Abe H, Tanaka K, Takatsu K, Sugamura K, Nakamura M, and Nagata K (2003). Gene structure and functional properties of mouse CRTH2, a prostaglandin D₂ receptor. *Biochem Biophys Res Commun* 307: 797-802.

Honda K, Arima M, Cheng G, Taki S, Hirata H, Eda F, Fukushima F, Yamaguchi B, Hatano M, Tokuhisa T, and Fukuda T (2003). Prostaglandin D₂ reinforces Th2 type inflammatory responses of airways to low-dose antigen through bronchial expression of macrophage-derived chemokine. *J Exp Med* 198: 533-543.

Matsuoka T, Hirata M, Tanaka H, Takahashi Y, Murata T, Kabashima K, Sugimoto Y, Kobayashi T, Ushikubi F, Aze Y, Eguchi N, Urade Y, Yoshida N, Kimura K, Mizoguchi A, Honda Y, Nagai H, and Narumiya S (2000). Prostaglandin D₂ as a mediator of allergic asthma. *Science* 287: 2013-2017.

Monneret G, Gravel S, Diamond M, Rokach J, and Powell WS (2001). Prostaglandin D₂ is a potent chemoattractant for human eosinophils that acts via a novel DP receptor. *Blood* 98: 1942-1948.

Mould AW, Matthaei KI, Young IG, and Foster PS (1997). Relationship between interleukin-5 and eotaxin in regulating blood and tissue eosinophilia in mice. *J Clin Invest* 99: 1064-1071.

Nagai H, Takeda H, Yamaguchi S, Tanaka H, Matsuo A, and Inagaki N (1995). The effect of a thromboxane A₂ receptor antagonist BAY-u-3405 on experimental allergic reactions. *Prostaglandins* 50: 75-87.

Nagata K, Hirai H, Tanaka K, Ogawa K, Aso T, Sugamura K, Nakamura M, and Takano S (1999a). CRTH2, an orphan receptor of T-helper-2-cells, is expressed on basophils and eosinophils and responds to mast cell-derived factor(s). *FEBS Lett* 459: 195-199.

Nagata K, Tanaka K, Ogawa K, Kemmotsu K, Imai T, Yoshie O, Abe H, Tada K, Nakamura M, Sugamura K, and Takano S (1999b). Selective expression of a novel

surface molecule by human Th2 cells in vivo. *J Immunol* 162: 1278-1286.

O'Sullivan S, Roquet A, Dahlen B, Dahlen S, and Kumlin M (1998). Urinary excretion of inflammatory mediators during allergen-induced early and late phase asthmatic reactions. *Clin Exp Allergy* 28: 1332-1339.

Oguma T, Asano K, Shiomi T, Fukunaga K, Suzuki Y, Nakamura M, Matsubara H, Sheldon HK, Haley KJ, Lilly CM, Drazen JM, and Yamaguchi K (2002). Cyclooxygenase-2 expression during allergic inflammation in guinea-pig lungs. *Am J Respir Crit Care Med* 165: 382-386.

Rothenberg ME, Ownbey R, Mehlhop PD, Loisel PM, van_de_Rijn M, Bonventre JV, Oettgen HC, Leder P, and Luster AD (1996). Eotaxin triggers eosinophil-selective chemotaxis and calcium flux via a distinct receptor and induces pulmonary eosinophilia in the presence of interleukin 5 in mice. *Mol Med* 2: 334-348.

Shichijo M, Sugimoto H, Nagao K, Inbe H, Encinas JA, Takeshita K, Bacon KB, and Gantner F (2003). Chemoattractant receptor-homologous molecule expressed on Th2 cells activation in vivo increases blood leukocyte counts and its blockade abrogates 13,14-dihydro-15-keto-prostaglandin D₂-induced eosinophilia in rats. *J Pharmacol Exp Ther* 307: 518-525.

Tanaka K, Hirai H, Takano S, Nakamura M, and Nagata K (2004). Effects of prostaglandin D₂ on helper T cell functions. *Biochem Biophys Res Commun* 316: 1009-1014.

Woodward DF, Hawley SB, Williams LS, Ralston TR, Protzman CE, Spada CS, and Nieves AL (1990). Studies on the ocular pharmacology of prostaglandin D₂. *Invest Ophthalmol Vis Sci* 31: 138-146.

Footnotes

Y.S. received a fellowship from the Foundation of the Association for Preventive Medicine of Japan. This study was partially supported by a grant-in-aid from the Japanese Ministry of Health, Labour and Welfare.

Reprint request to Koichiro Asano, M. D. Division of Pulmonary Medicine, Department of Medicine, Keio University School of Medicine, 35 Shinanomachi, Shinjuku-ku, Tokyo 160-8582, Japan

Figure Legends

Figure 1.

Total and differential leukocyte counts in BAL fluid.

BAL was performed at two hours after intratracheal administration of PGD₂ (100 nmoles/animal) or vehicle in IL-5 (0.2 ng/kg)- or PBS-pretreated animals. PBS/vehicle group (open bars, n = 3), IL-5/vehicle group (hatched bars, n = 10), PBS/PGD₂ group (dotted bars, n = 4), IL-5/PGD₂ group (closed bars, n = 11). Mean + SEM. **: p < 0.01, compared to PBS/vehicle group.

Figure 2.

Kinetics of eosinophils in peripheral blood.

Rats received intravenous injection of IL-5 or PBS one hour prior to intratracheal administration of PGD₂ (100 nmoles/animal) or vehicle (time 0). Peripheral blood samples were obtained every hour after administration of IL-5, and the number of eosinophils was counted. PBS/vehicle group (closed circles, n = 3), IL-5/vehicle group (open circles, n = 3), PBS/PGD₂ group (closed triangles, n = 3), IL-5/PGD₂ group (open triangles, n = 3). Mean + SEM. *: p < 0.05, compared to PBS/vehicle group.

Figure 3.

(A) PGD₂ dose-response of BAL eosinophilia two hours after intratracheal administration of PGD₂. PGD₂ (1 - 100 nmoles/animal) increased the number of eosinophils in BAL fluid from IL-5-pretreated rats in a dose-dependent manner. n = 3 - 11. *: p < 0.05, **: p < 0.01, compared to vehicle-injected animals.

(B) Time course of BAL eosinophilia following intravenous IL-5/intratracheal PGD₂

(100 nmoles/animal) treatment. PBS/vehicle group (open bars, $n = 3 - 7$), IL-5/PGD₂ group (hatched bars, $n = 3 - 11$). Mean + SEM. **: $p < 0.01$, compared to PBS/vehicle group.

Figure 4.

Effects of various prostanoid receptor agonists on BAL eosinophilia. BAL was performed two hours after PGD₂ ($n = 11$), CRTH2 agonist (DK-PGD₂, MK-PGD₂, indomethacin, $n = 6$ each), DP agonist (BW 245C, $n = 6$), TP agonist (I-BOP, $n = 3$) or vehicle ($n = 10$) was administered intratracheally in IL-5-pretreated animals. All the agonists were administered at a dose of 100 nmoles/animal. Mean + SEM. **: $p < 0.01$, compared to vehicle group.

Figure 5.

(A) Effects of various prostanoid receptor antagonists on BAL eosinophilia in IL-5/PGD₂-treated rats. Either CRTH2/TP antagonist (ramatroban, 3 - 10 mg/kg p.o., $n = 3$ each), TP antagonist (SQ29,548, 2.5 mg/kg i.v., $n = 3$), DP antagonist (BW A868C, 1 mg/kg i.v., $n = 5$), or vehicle ($n = 4$) was administered two hours prior to intratracheal injection of PGD₂. PBS-based vehicle, instead of PGD₂, was administered intratracheally in the PBS group ($n = 10$). Mean + SEM. *: $p < 0.05$, **: $p < 0.01$, compared to PBS group. ††: $p < 0.01$, compared to vehicle group.

(B) Effects of ramatroban on CRTH2 agonist-induced BAL eosinophilia. Either ramatroban (hatched columns, 10 mg/kg p.o., $n = 3 - 7$) or vehicle (closed columns, $n = 6 - 11$) was administered one hour prior to intratracheal injection of CRTH2 agonist (100 nmoles/animal). Mean + SEM. **: $p < 0.01$, compared to vehicle group.

Figure 6.

Histological examination of lungs from rats treated with intravenous IL-5 (0.2 ng/kg), intratracheal PGD₂ (100 nmoles/animal), or both. Giemsa stain. PBS/vehicle (A), PBS/PGD₂ (B), IL-5/vehicle (C), IL-5/PGD₂ (D). Original magnification, x100. V: vessel, B: bronchus.

Figure 7.

Semi-quantitative histological scoring of eosinophil accumulation in peribronchial (A) and perivascular (B) spaces. The degree of eosinophil accumulation in each bronchus or vessel was graded from 0 (no eosinophils) to 4 (marked eosinophil infiltration). Five bronchi and vessels were evaluated in each side of lungs, and the total lung score (0 - 40) represents the sum of the scores of both lungs. Bars represent mean values. n = 4 each. **: p < 0.01, compared to PBS/vehicle group.

Figure 1

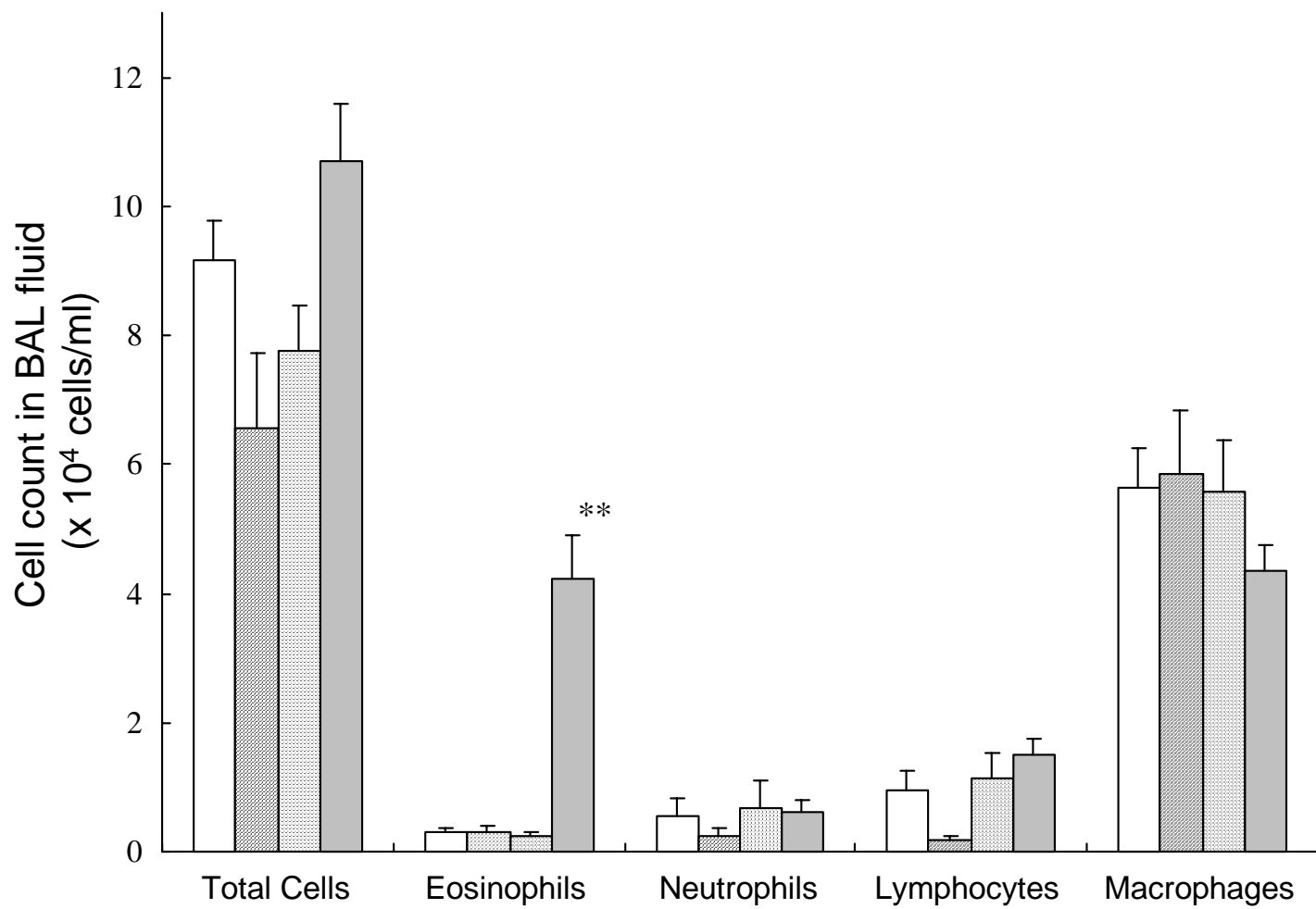


Figure 2

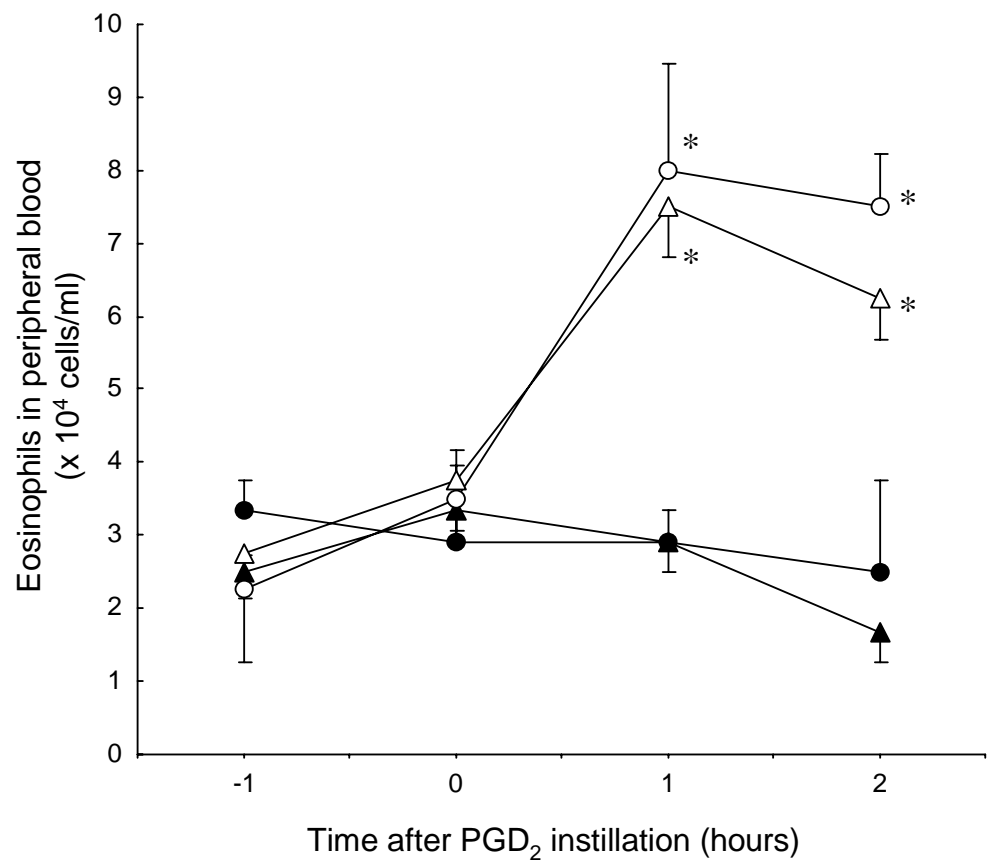


Figure 3

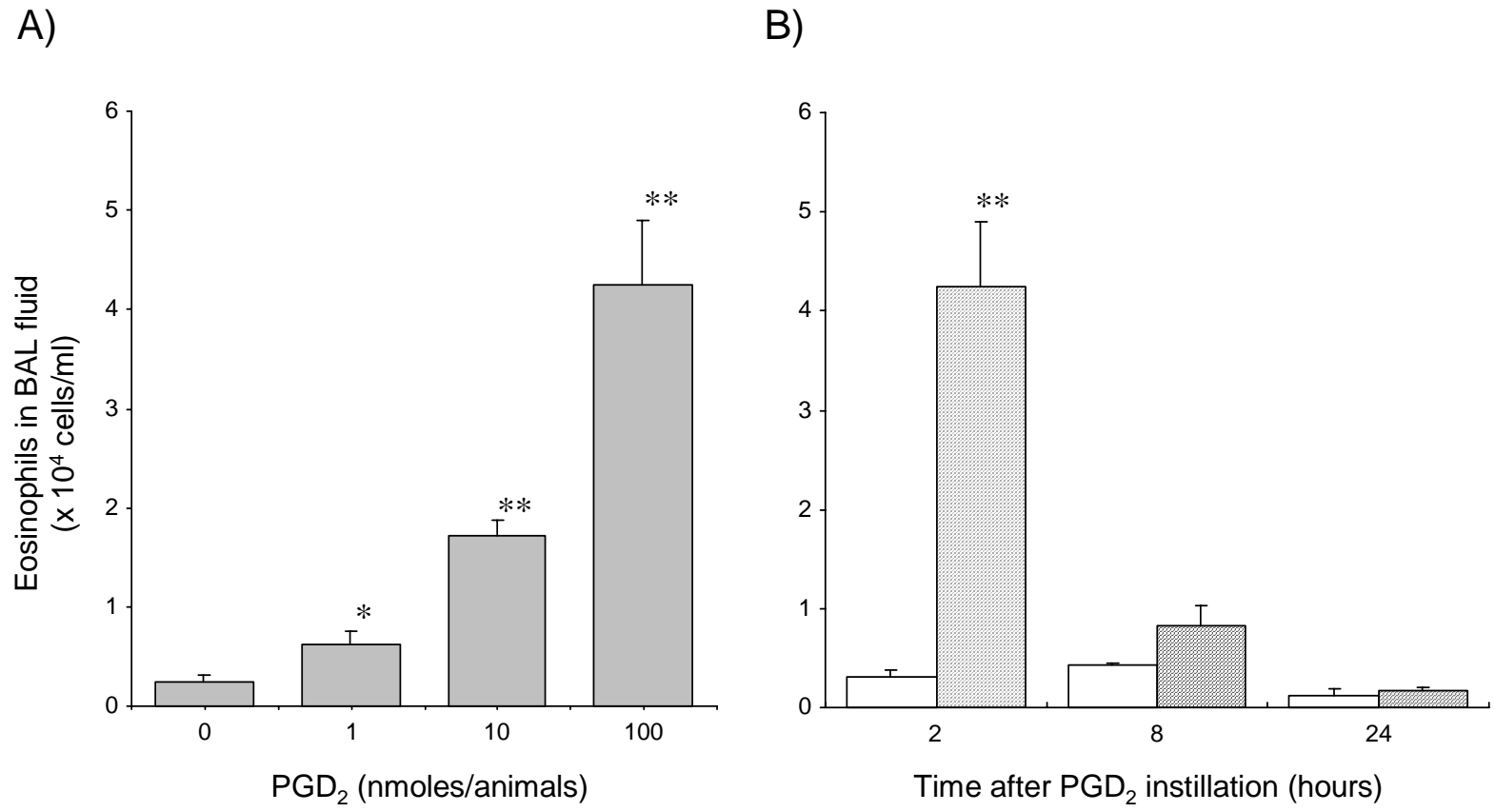


Figure 4

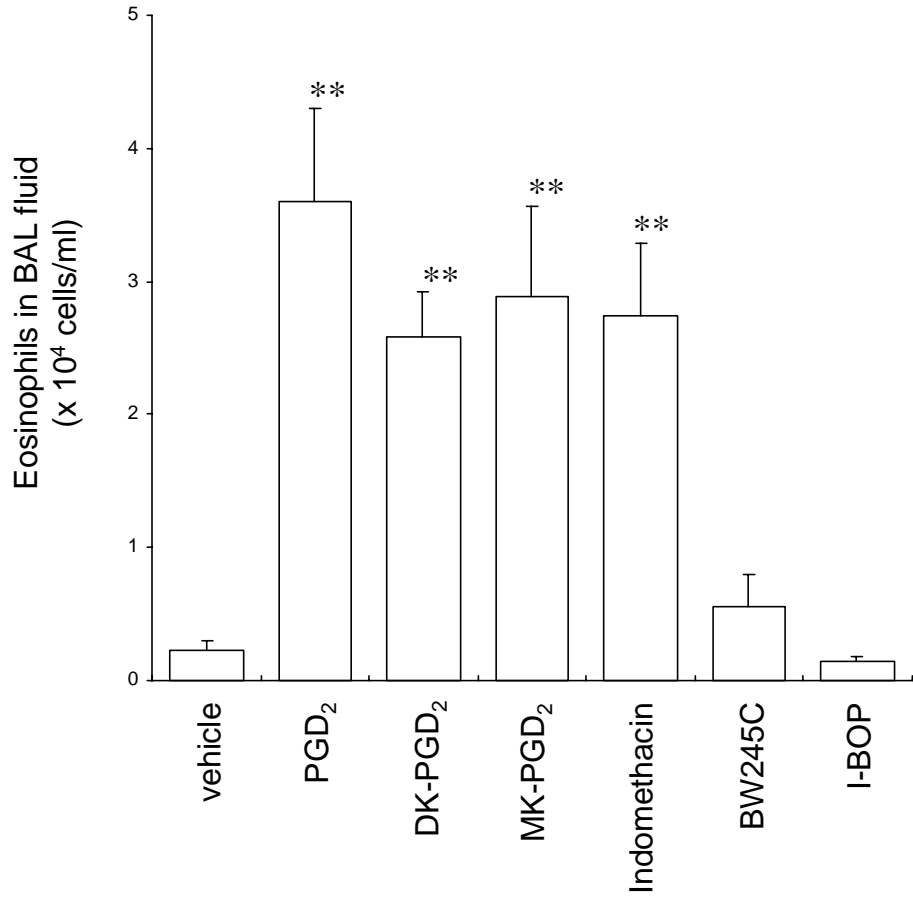


Figure 5

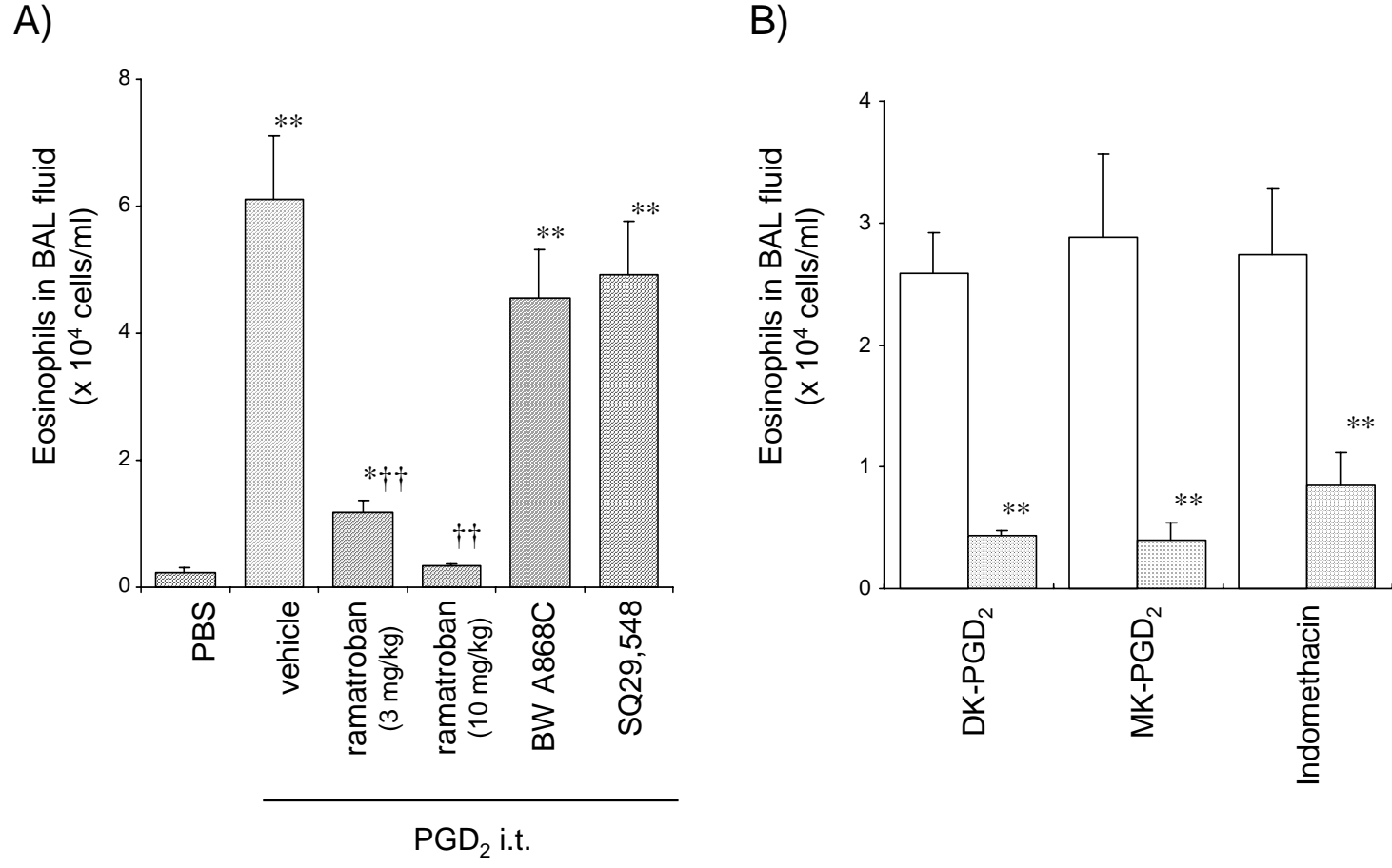


Figure 6

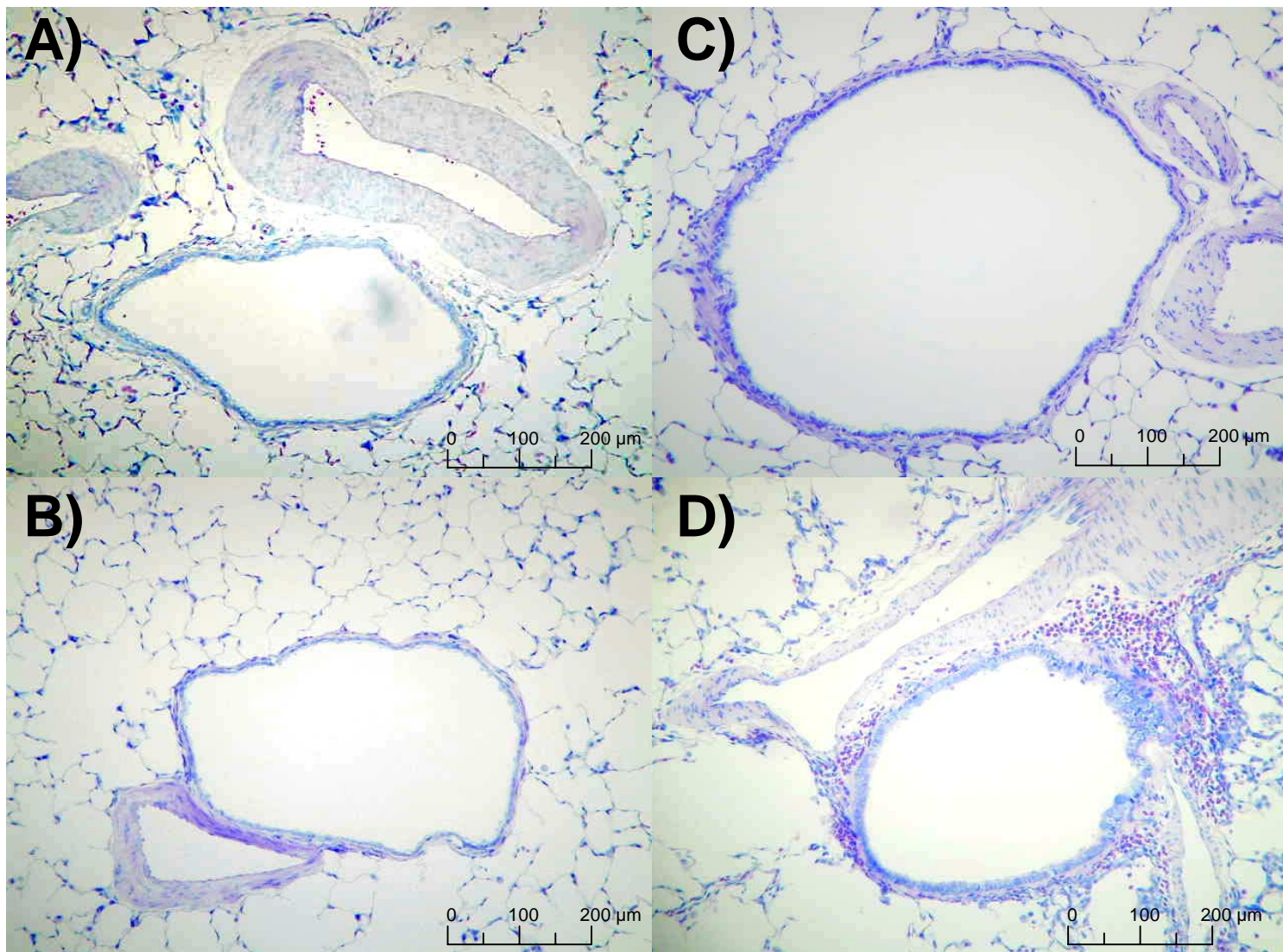


Figure 7

