Sustained exposure to prostaglandin D$_2$ augments the contraction induced by acetylcholine via a DP$_1$ receptor-mediated activation of p38 in bronchial smooth muscle of naive mice

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Abstract

Prostaglandin D$_2$ (PGD$_2$), one of the key lipid mediators of allergic airway inflammation, is increased in the airways of asthmatics. However, the role of PGD$_2$ in the pathogenesis of asthma is not fully understood. In the present study, effects of PGD$_2$ on smooth muscle contractility of the airways were determined to elucidate its role in the development of airway hyperresponsiveness (AHR). In a murine model of allergic asthma, antigen challenge to the sensitized animals caused a sustained increase in PGD$_2$ levels in bronchoalveolar lavage (BAL) fluids, indicating that smooth muscle cells of the airways are continually exposed to PGD$_2$ after the antigen exposure. In bronchial smooth muscles (BSMs) isolated from naive mice, a prolonged incubation with PGD$_2$ ($10^{-5}$ M, for 24 h) induced an augmentation of contraction induced by acetylcholine (ACh): the ACh concentration-response curve was significantly shifted upward by the 24-h incubation with PGD$_2$. Application of PGD$_2$ caused phosphorylation of ERK1/2 and p38 in cultured BSM cells: both of the PGD$_2$-induced events were abolished by laropiprant (a DP$_1$ receptor antagonist) but not by fevipiprant (a DP$_2$ receptor antagonist). In addition, the BSM hyperresponsiveness to ACh induced by the 24-h incubation with PGD$_2$ was significantly inhibited by co-incubation with SB203580 (a p38 inhibitor), whereas U0126 (a ERK1/2 inhibitor) had no effect on it. These findings suggest that prolonged exposure to PGD$_2$ causes the BSM hyperresponsiveness via the DP$_1$ receptor-mediated activation of p38. A sustained increase in PGD$_2$ in the airways might be a cause of the AHR in allergic asthmatics.

Key words: airway hyperresponsiveness, bronchial smooth muscle contractility, prostaglandin D$_2$ (PGD$_2$), DP$_1$ receptor, p38
Introduction

Heightened responsiveness to non-specific stimuli of the airways, called airway hyperresponsiveness (AHR), is a characteristic feature in patients with allergic asthma. It has been suggested that the augmented contraction of airway smooth muscle is one of the causes of the AHR (1–5). Clinical observation that the inhalation of short-acting β₂-stimulant is largely effective for airway limitation in asthma attack also suggests an increased airway smooth muscle contraction in the airway obstruction. It is thus important for development of asthma therapy to understand the disease-related changes in the contractile signaling of airway smooth muscle cells.

In allergic asthma, an involvement of prostaglandin D₂ (PGD₂), one of the cyclooxygenase (COX) metabolites that released from mast cells in allergic reaction, has been suggested in its pathogenesis. In animal models of allergic asthma, the PGD₂ levels in bronchoalveolar lavage (BAL) fluids were increased (6–8). In people with asthma, an increase in PGD₂ in BAL fluids was observed after allergen challenge to the airways (9, 10). An involvement of PGD₂ in the allergic inflammation, including the airway inflammation in asthma, has also been suggested. In a DP₁ receptor (one of the receptors for PGD₂) gene knockout mice, both cytokines increase in BAL fluids and airway eosinophilia induced by allergen challenge were weakened as compared to wild-type animals (11). In Th2 lymphocytes, PGD₂ also has an ability to cause cytokine release via an activation of DP₂ receptor (also called as CRTH2 receptor) (12). However, the functional role of PGD₂ on airway smooth muscle remains largely unclear.

We show here that PGD₂ levels in the airways were increased immediately after antigen challenge and were sustained during the development of antigen-induced AHR. To imitate the antigen-induced sustained increase in PGD₂ in vitro, the BSM tissues isolated from naive mice were incubated with PGD₂ for 24 h. Using the PGD₂-treated BSM tissues, change in the BSM contractility was evaluated by measuring isometric contractions induced by acetylcholine (ACh) and high K⁺ depolarization. The receptor subtypes and signaling molecules involved in the PGD₂-induced BSM hyperresponsiveness were also identified pharmacologically.

Methods

Animals

Male BALB/c mice were purchased from Tokyo Laboratory Animals Science Co., Ltd. (Tokyo, Japan) and housed in a pathogen-free facility. All animal experiments were approved by the Animal Care Committee of Hoshi University (Tokyo, Japan).

Sensitization and antigenic challenge

Preparation of a murine model of allergic bronchial asthma, which has an in vivo AHR (13), was performed as described previously (14). In brief, BALB/c mice (8 weeks of age) were actively sensitized by intraperitoneal injections of 8 µg ovalbumin (OA; Sigma-Aldrich, St. Louis, MO, USA) with 2 mg Imject Alum (Pierce Biotechnology, Inc., Rockfold, IL, USA) on day 0 and day 5. The sensitized mice were challenged with aerosolized OA-saline solution (5 mg/ml) for 30 min on days 12, 16 and 20. A control group of mice received the same immunization procedure but inhaled saline aerosol instead of OA challenge. The aerosol was generated with a Mini Elite nebulizer (Philips Respironics, Amsterdam, Netherlands) and introduced to a Plexiglas chamber box (130 × 200 mm, 100 mm height) in which the mice were placed. Mice were sacrificed 1, 3, 6, 12 and 24 h after the last challenge by exsanguination from abdominal aorta under urethane (1.6 g/kg, i.p.;Sigma, St. Louis, MO, USA) anesthesia.
RNA extraction from bronchial smooth muscle (BSM) tissues

Total RNA of the mouse BSM tissue was isolated from an aliquot of the tissue using NucleoSpin™ miRNA (TaKaRa Bio, Inc., Shiga, Japan) according to the manufacturer’s instruction. cDNAs were prepared from the total RNA by using PrimeScript™ RT reagent Kit (TaKaRa) according to the manufacturer’s instruction.

Real-time RT-PCR

The mRNA levels were examined by real-time RT-PCR. cDNA was subjected to real-time PCR analyses using Fast SYBR Green Master Mix (Applied biosystems, Foster, CA, USA) according to the manufacturer’s instruction. The PCR primer sets used are shown in Table 1, which was designed from published database, BLAST. The thermal cycle profile used was 1) denaturing for 3 s at 95 °C, 2) annealing and extending the primers for 30 s at 60 °C, and the reaction was run for 43 cycles.

Analyses of bronchoalveolar lavage fluids

After the exsanguinations, the chest of each animal was opened and a 20-gauge blunt needle was tied into the proximal trachea. Bronchoalveolar lavage fluids (BALFs) was obtained by intratracheal instillation of 1 ml/animal of phosphate-buffered saline (PBS; pH7.5, room temperature) into the lung while it was kept located within the thoracic cavity. The lavage was reinfused into the lung twice before final collection. The resultant supernatants of the lavage fluids were subjected to protein analyses. The level of PGD₂ was measured by Prostaglandin D₂-MOX, EIA Kit (Cayman Chemical Company, Ann Arbor, MI, USA), according to the manufacturer’s instructions.

Determination of bronchial smooth muscle (BSM) responsiveness

Mice were killed by exsanguination from abdominal aorta under urethane (1.6 g/kg, i.p.) anesthesia. Then the airway tissues under the larynx to lungs were immediately removed. About 3 mm length of the left main bronchus was isolated. The resultant tissue ring preparation was then suspended in a 5 ml-organ bath by two stainless-steel wires (0.2 mm diameter) passed through the lumen. For all tissues, one end was fixed to the bottom of the organ bath while the other was connected to a force-displacement transducer (TB-612T, Nihon Kohden) for the measurement of isometric force. A resting tension of 5.0 mN was applied. The buffer solution contained modified Krebs-Henseleit solution with the following composition (mM); NaCl 118.0, KCl 4.7, CaCl₂ 2.5, MgSO₄ 1.2, NaHCO₃ 25.0, KH₂PO₄ 1.2 and glucose 10.0. The buffer solution was maintained at 37°C and oxygenated with 95% O₂-5% CO₂. After the equilibration period, the concentration-response curve to ACh (10⁻⁷–10⁻³ M in final concentration) was constructed cumulatively. In another series of experiment, isotonic K⁺

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Table 1. Primer sequences for RT-PCR used in the present study

<table>
<thead>
<tr>
<th>Gene name</th>
<th>RefSeq Accession</th>
<th>Sequence</th>
<th>Amplicon size</th>
</tr>
</thead>
<tbody>
<tr>
<td>mouse Pla2g4c</td>
<td>NM_001168504</td>
<td>Sense 5’-GGACCGTTGGCTTTTGTGA-3’</td>
<td>150 bp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Antisense 5’-GCAAACCAGCATCCACCAG-3’</td>
<td></td>
</tr>
<tr>
<td>mouse Ptgs2</td>
<td>NM_0011198</td>
<td>Sense 5’-CCGGGGAATGTAGAGCA-3’</td>
<td>128 bp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Antisense 5’-GGGTTGGTTCAGCATATGAA-3’</td>
<td></td>
</tr>
<tr>
<td>mouse Hpgds</td>
<td>NM_019455</td>
<td>Sense 5’-TTCCCATGCGAAGAAGA-3’</td>
<td>143 bp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Antisense 5’-GCCCAAGTTACATAATGCTC-3’</td>
<td></td>
</tr>
<tr>
<td>mouse Gapdh</td>
<td>NM_008084</td>
<td>Sense 5’-CTCGTCCCCGATGACAAATG-3’</td>
<td>100 bp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Antisense 5’-CTCCACTTTTGGCCACTGCA-3’</td>
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</tbody>
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solution (10–90 mM in final concentration) was cumulatively administrated in the presence of atropine (10⁻⁶ M) to determine the BSM responsiveness to high K⁺-depolarization.

**Tissue culture of isolated bronchial smooth muscles (BSMs)**

After the determination of BSM responsiveness described above, the tissue preparations were immediately immersed in SmBM™ Medium (SmBM; Cambrex Bio Science Walkersville, Inc., MD, USA) containing 50 U/ml penicillin and 50 µg streptomycin (Invitrogen Corp., Grand Island, NY, USA) and cultured at 37 °C under a 5% CO₂ atmosphere in the presence or absence of PGD₂ (Cayman Chemical Company) for 24 h. After the incubation period, BSM responsiveness was determined as described above. In another series of experiments, the 24-h PGD₂ incubation was carried out in the presence or absence of pharmacological agent. The agents used in the present study were U0126, an ERK1/2 inhibitor (15), and SB203580, a p38 inhibitor (16).

**Cell culture and sample collection**

Normal human BSM cells (hBSMCs; Cambrex Bio Sience Walkersville, Inc., Walkersville, MD, USA) were maintained in SmBM medium supplemented with 5% fetal bovine serum, 0.5 ng/ml human epidermal growth factor (hEGF), 5 µg/ml insulin, 2 ng/ml human fibroblast growth factor-basic (hFGF-b), 50 µg/ml gentamicin and 50 µg/ml amphotericin B. Cells were maintained at 37 °C in a humidified atmosphere (5% CO₂), fed every 48–72 h, and passaged when cells reached 90–95% confluence. Then the hBSMCs (passages 4–7) were seeded in 6-well plates (Becton Dickinson Labware, Franklin Lakes, NJ, USA) at density of 3,500 cells/cm² and, when 80–85% confluence was observed, cells were cultured without serum for 24 h before the addition of PGD₂. At the indicated time after the treatment with PGD₂, hBSMCs were immediately collected and disrupted with 1× SDS sample buffer (150 µl/well), and used for Western blot analyses.

**Western blot analyses**

Protein samples were subjected to 15% sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) and the proteins were then electrophoretically transferred to PVDF membrane. After blocking with EzBlock Chemi (ATTO, Japan), the PVDF membrane was incubated with the primary antibody. The primary antibodies used in the present study were monoclonal mouse anti-phospho-ERK1/2 (1:1,000 dilution; Santa Cruz Biotechnology, Inc., Santa Cruz, CA, USA), anti-ERK1/2 (1:1,000 dilution; Santa Cruz Biotechnology, Inc.) and monoclonal rabbit anti-phospho-p38 (1:10,000 dilution; Cell Signaling Technology Japan) antibodies. Then the membrane was incubated with HRP-linked anti-rabbit IgG (1:5,000 dilution; Cell Signaling Technology Japan) or anti-mouse IgG (1:5,000 dilution; Santa Cruz Biotechnology, Inc.).

**Statistical analyses**

All the data are expressed as the mean ± S.E.M. Statistical significance of difference was determined by one-way analysis of variance (ANOVA) with post hoc Bonferroni/Dunn or two-way ANOVA (PrismTM 5 for Mac OS X; GraphPad Software, Inc., La Jolla, CA, USA). A value of P<0.05 was considered to be significant.

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**Results**

**Change in prostaglandin D₂ (PGD₂) production in the airways after antigen exposure**

In the present study, we used our well-established murine model of allergic bronchial asthma (13, 14, 17–19). In this animal model of asthma, mRNAs for Pla2g4c (phospholipase A₂ group 4c), Ptgs2 (cyclooxygen-
Sustained PGD$_2$ exposure augments BSM contractility

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**Effects of a 24-h incubation with prostaglandin D$_2$ (PGD$_2$) on bronchial smooth muscle (BSM) contractility**

The findings that PGD$_2$ levels in BALFs sustainedly increased (Fig. 2) indicate that smooth muscle cells of the airways are continually exposed to PGD$_2$. To imitate the antigen-induced sustained increase in PGD$_2$ in vitro, the BSM tissues isolated from naïve mice were incubated with PGD$_2$ for 24 h as described above. As shown in Fig. 3A, in the BSM tissues isolated from naïve animals, the 24-h incubation with PGD$_2$ caused a hyperresponsiveness to acetylcholine (ACh): the ACh concentration-response curve was significantly shifted upward by the 24-h PGD$_2$ incubation ($P<0.01$ by two-way ANOVA; Fig. 3A). On the other hand, no significant change in the contractile responsiveness to high K$^+$ depolarization (in the presence of 10$^{-6}$ M atropine) was observed in the PGD$_2$-incubated BSM tissues (Fig. 3B).
Phosphorylation of ERK1/2 and p38 by prostaglandin D$_2$ (PGD$_2$) in bronchial smooth muscle (BSM) cells

To identify the signaling molecules activated by PGD$_2$ in the BSM cells, cultured BSM cells were stimulated with PGD$_2$. As shown in Fig. 4, immunoblot analyses revealed that PGD$_2$ caused a distinct phosphorylation of ERK1/2 and p38, i.e., activation of these molecules, in the BSM cells. Both the PGD$_2$-induced phos-
Sustained PGD₂ exposure augments BSM contractility

Phorylation of ERK1/2 and p38 were abolished by laropiprant (a DP₁ receptor antagonist), whereas fevipiprant (a DP₂ receptor antagonist) had no effect on their phosphorylation (Fig. 4). On the other hand, in the BSM cells, PGD₂ did not cause activation of other molecules, such as JNK and STAT3 (data not shown), that were reportedly activated in various types of the cells (7, 20–23).

**Effects of inhibitors for ERK1/2 and p38 on the bronchial smooth muscle (BSM) hyperresponsiveness induced by prostaglandin D₂ (PGD₂)**

To determine the roles of ERK1/2 and p38 on the BSM hyperresponsiveness induced by PGD₂, the BSM tissues isolated from naive mice were co-incubated with an ERK1/2 inhibitor U0126 or a p38 inhibitor SB203580 during the 24-h PGD₂ incubation period. As shown in Fig. 5A, co-incubation with U0126 had no significant effect on the ACh responsiveness in the 24-h PGD₂-incubated BSMs. However, the BSM hyperresponsiveness to ACh induced by the 24-h PGD₂ incubation was attenuated by the co-incubation with SB203580 (Fig. 5B): the ACh concentration-response curve was significantly shifted downward when the BSM tissues were incubated in the presence of SB203580 (P<0.01 by two-way ANOVA; Fig. 5B).

**Discussion**

Consistently with the previous report (8), the mRNA expressions for Pla2g4c, Ptgs2 and Hpgds were significantly increased in the bronchial smooth muscle (BSM) tissues (Fig. 1), indicating that arachidonic acid...
metabolism is shifted towards prostaglandin D_2 (PGD_2) production in mice with allergic asthma. Indeed, a sustained increase in PGD_2 was observed in the airways after the antigen stimulation (Fig. 2). The BSM hyperresponsiveness reported in experimental asthma (14, 18) was replicated when the BSM tissues isolated from naive animals were incubated with PGD_2 for 24 h (Fig. 3). PGD_2 caused phosphorylation of ERK1/2 and p38 in the BSM cells via an activation of DP_1 receptor (Fig. 4). The BSM hyperresponsiveness induced by the 24-h PGD_2 incubation was inhibited by a p38 inhibitor SB203580, but not by an ERK1/2 inhibitor U0126 (Fig. 5). These findings suggest that a sustained increase in PGD_2 level in the airways is a cause of the AHR in asthma, and that the DP_1-mediated activation of p38 is responsible for the BSM hyperresponsiveness induced by PGD_2.

Our previous microarray analysis of differentially expressed genes (GEO accession No. GSE116504) demonstrated a significant change in the arachidonic acid (AA) metabolism pathway (KEGG map00590) in the BSM tissues of asthma (8). In particular, the AA metabolism was largely shifted towards PGD_2 production in the diseased BSMs (8). Currently, time-course studies of the gene expression revealed that Pla2g4c, Ptgs2 and Hpgds were up-regulated in the relatively early period after antigen challenge (Fig. 1). Notably, time-course change of the PGD_2 level in BALF (Fig. 2) seems to be parallel with that of up-regulation of Hpgds (Fig. 1C), indicating that the hematopoietic prostaglandin D synthase (HPGDS) is responsible for the increased PGD_2 production in the diseased airways. The idea is also supported by the observation that the lipocalin-type PGDS (LPGDS), one of the two types of PGDS, expression was not changed in the diseased BSM tissues in the microarray analysis (GSE116504).
The current time-course study also revealed a sustained increase in PGD$_2$ in the airways: the PGD$_2$ levels in BALFs were already increased just after the antigen exposure (Fig. 2). The findings indicate that smooth muscle cells of the airways are continually exposed to PGD$_2$, and remind us of an idea that the sustained increase in PGD$_2$ might be a cause of augmented BSM contractility at the AHR. Indeed, consistently with the previous report (8), the 24-h incubation with PGD$_2$ induced a hyperresponsiveness to ACh in the BSM tissues isolated from naive animals (Fig. 3A). PGD$_2$ had no effect on contractile responsiveness to high K$^+$ depolarization (in the presence of 10$^{-6}$ M atropine, to block the effect of endogenously released ACh: Fig. 3B). In the antigen-induced AHR mice, an augmented BSM contractility to ACh without alteration of high K$^+$ responsiveness has also been observed (14, 18). It is thus possible that PGD$_2$ is one of the factors that contribute to the altered property of BSMs in allergic asthma.

To identify the signaling molecule(s) activated by PGD$_2$ in BSM cells, cultured human BSM cells (hBSMCs) were stimulated with PGD$_2$. Because the mouse BSM tissue contains various types of cells other than the BSM cells, the commercially available hBSMCs were used in the present study. Reportedly, PGD$_2$ has an ability to activate various signaling molecules, such as ERK1/2, p38, JNK, and STAT3 (7, 20–23). Among these molecules, the current immunoblot analyses revealed that PGD$_2$ caused a distinct activation of ERK1/2 and p38, i.e., phosphorylation of these proteins, in the hBSMCs (Fig. 4). The findings are consistent with the previous report, in which phosphorylation of these molecules induced by PGD$_2$ were demonstrated in a human BSM cell line, BSM2146 cells (7). To date, two distinct receptor subtypes for PGD$_2$, termed DP$_1$ and DP$_2$ receptors, have been identified (24–26). To identify receptor subtype responsible for the phosphorylation of ERK1/2 and p38 induced by PGD$_2$, the hBSMCs were pre-incubated with a DP$_1$ antagonist laropiprant (27) or a DP$_2$ antagonist fevipiprant (28) during the PGD$_2$ stimulation. As a result, both the PGD$_2$-induced phosphorylation of ERK1/2 and p38 were abolished by laropiprant, whereas fevipiprant had no effect on their phosphorylation (Fig. 4). Thus, PGD$_2$ acts on DP$_1$ receptors to activate ERK1/2 and p38 in BSM cells.

The results that PGD$_2$ activated ERK1/2 and p38 in the BSM cells suggest an involvement of these signaling molecules in the augmented BSM responsiveness to ACh. Indeed, activation of these molecules could cause an augmentation of the contraction in airway smooth muscles (29–32). To determine the roles of ERK1/2 and p38 on the BSM hyperresponsiveness induced by PGD$_2$, the BSM tissues isolated from naive mice were co-incubated with an ERK1/2 inhibitor U0126 (15) or a p38 inhibitor SB203580 (16) during the 24-h PGD$_2$ incubation period. As shown in Fig. 5, although U0126 had no significant effect (Fig. 5A), the BSM hyperresponsiveness to ACh induced by PGD$_2$ was attenuated by the co-incubation with SB203580 (Fig. 5B): the ACh concentration-response curve was significantly shifted downward when the BSM tissues were incubated in the presence of SB203580 (Fig. 5B). The findings strongly suggest that the PGD$_2$-induced BSM hyperresponsiveness is mediated by an activation of p38.

The current study clearly demonstrated that the 24-h incubation with PGD$_2$ caused an augmented BSM contractility to ACh (Fig. 3). The results indicate that PGD$_2$ acts on DP$_1$ receptor on the BSMs to activate p38 (Figs. 4 and 5), resulting in the induction of BSM hyperresponsiveness. On the other hand, some of the PGD$_2$ metabolites may also be involved in the BSM hyperresponsiveness. PGD$_2$ is known to convert to PGJ$_2$ family of prostanoids (33), and their physiological and pathophysiological roles have also been suggested. For example, a PGD$_2$ metabolite 15-deoxy-$\Delta^{12,14}$-prostaglandin J$_2$ (15-deoxy PGJ$_2$) has an ability to activate signaling molecules, such as peroxisome proliferator-activated receptor-$\gamma$ (PPAR-$\gamma$) (34) and phosphoinositide 3-kinase (PI3 K)-Akt (35). Interestingly, exogenously applied 15-deoxy PGJ$_2$ could inhibit airway inflammation and hyperresponsiveness in murine models of allergic asthma (36). Further studies are needed to make clear the exact role of PGD$_2$ on the development of BSM hyperresponsiveness in allergic asthma.
Again, the current study revealed that PGD$_2$ caused a phosphorylation of p38 in the BSM cells via an activation of DP$_1$ receptor (Fig. 4B). The BSM hyperresponsiveness induced by the 24-h PGD$_2$ incubation was inhibited by a p38 inhibitor SB203580 (Fig. 5B). These findings indicate that the DP$_1$-mediated activation of p38 is responsible for the BSM hyperresponsiveness induced by PGD$_2$. However, it is well known that the DP$_1$ is a Gs protein-coupled receptor. In smooth muscle cells including the airways, the Gs protein activation causes an inhibition of the contraction via an increase in cAMP level (e.g., 37–39). Indeed, PGD$_2$ reportedly induced a relaxation via an activation of DP$_1$ receptor in the tracheal smooth muscles pre-contracted with carbachol (11). In contrast, PGD$_2$ also elicited a contraction of the airway smooth muscle (8, 40–42) probably via an activation of DP$_1$ receptor (42). Although the contrariety is not explainable currently, the DP$_1$ receptor stimulation with PGD$_2$ may primarily activate signaling molecules other than the cAMP-dependent relaxing ones, resulting in an augmentation of the BSM contraction.

A small GTPase RhoA is a key protein that mediates sensitization of smooth muscle contraction including the airways (43, 44). In the BSMs of experimental asthma, an augmentation of agonist-induced RhoA-mediated Ca$^{2+}$ sensitization has been demonstrated (14, 18, 45). No change in the contraction mediated solely by cytosolic Ca$^{2+}$, such as the contraction induced by high K$^+$ depolarization, has also been demonstrated in the diseased BSMs (14, 18). The current findings that PGD$_2$ augmented the contraction induced by ACh, but not by high K$^+$ depolarization (Fig. 3), also support an idea that PGD$_2$ may augment the RhoA-mediated Ca$^{2+}$ sensitization of contraction. Indeed, our previous study demonstrated that PGD$_2$ has an ability to activate RhoA in the BSMs (42). However, in our preliminary study, the 24-h incubation with PGD$_2$ did not cause the RhoA up-regulation, that is often observed in BSMs of experimental asthma (14, 18, 45).

As described above, our previous study demonstrated that PGD$_2$ has an ability to activate RhoA/Rho-kinase signaling: the Ca$^{2+}$ sensitization of contraction was augmented in the presence of PGD$_2$ (42). Currently, the BSM tissues were incubated with PGD$_2$ for 24 h, and their contractile responses were then measured after washing out PGD$_2$. Nevertheless, in the ABSENCE of PGD$_2$, the BSM responsiveness to ACh, but not to high K$^+$ depolarization, was significantly augmented (Fig. 3). On the other hand, the 24-h PGD$_2$ incubation did not cause the RhoA up-regulation (see above). Taken together, the sustained exposure to PGD$_2$ may up-regulate signaling molecule(s) other than RhoA activated by the muscarinic receptor stimulation. Further studies are needed to identify the mechanism of BSM hyperresponsiveness induced by the sustained exposure to PGD$_2$.

In conclusion, the current study demonstrated that the 24-h incubation with PGD$_2$ caused an augmentation of contraction in BSMs isolated from naive mice. The pharmacological study also revealed an involvement of DP$_1$ receptor-mediated activation of p38 in the BSM hyperresponsiveness induced by PGD$_2$. Thus, a sustained increase in PGD$_2$ in the airways might be a cause of the AHR in allergic asthmatics.

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**Conflict of Interest**

None of the authors have a financial relationship with a commercial entity that has an interest in the subject of this manuscript.
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