**Leukotriene E_{4}–induced pulmonary inflammation is mediated by the P2Y_{12} receptor**

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Of the potent lipid inflammatory mediators comprising the cysteiny- leukotrienes (LTs; LTC_{4}, LTD_{4}, and LTE_{4}), only LTE_{4} is stable and abundant in vivo. Although LTE_{4} shows negligible activity at the type 1 and 2 receptors for cys-LTs (CysLT_{1R} and CysLT_{2R}), it is a powerful inducer of mucosal eosinophilia and airway hyperresponsiveness in humans with asthma. We show that the adenosine diphosphate (ADP)–reactive purinergic (P2Y_{12}) receptor is required for LTE_{4}–mediated pulmonary inflammation. P2Y_{12} receptor expression permits LTE_{4}–induced activation of extracellular signal–regulated kinase in Chinese hamster ovary cells and permits chemokine and prostaglandin D_{2} production by LAD2 cells, a human mast cell line. P2Y_{12} receptor expression by LAD2 cells is required for competition between radiolabeled ADP and unlabeled LTE_{4} but not for direct binding of LTE_{4}, suggesting that P2Y_{12} complexes with another receptor to recognize LTE_{4}. Administration of LTE_{4} to the airways of sensitized mice potentiates eosinophilia, goblet cell metaplasia, and expression of interleukin–13 in response to low-dose aerosolized allergen. These responses persist in mice lacking both CysLT_{1R} and CysLT_{2R} but not in mice lacking P2Y_{12} receptors. The effects of LTE_{4} on P2Y_{12} in the airway were abrogated by platelet depletion. Thus, the P2Y_{12} receptor is required for proinflammatory actions of the stable abundant mediator LTE_{4} and is a novel potential therapeutic target for asthma.

Cysteinyl leukotrienes (LTs [cys-LTs]) are lipid inflammatory mediators generated in vivo by mast cells (MCs), eosinophils, myeloid DCs, basophils, and macrophages (Kanaoka and Boyce, 2004). They abound in mucosal inflammation, play a validated role in human asthma (Wenzel et al., 1990; Israel et al., 1996; Liu et al., 1996), and are important mediators in mouse models of pulmonary inflammation, remodeling, and fibrosis (Beller et al., 2004; Henderson et al., 2006; Kim et al., 2006). LTC_{4}, the parent cys-LT, is synthesized from arachidonic acid, which is liberated by calcium–dependent cPLA_{2} (cytosolic phospholipase A_{2}) from membrane phospholipids (Clark et al., 1991). Arachidonic acid is then converted to LTA_{4} by 5-lipoxygenase–dependent protein 1β (5-LO)–mediated removal of glutamyl LT; Der f, Dermatophagoides farinae; ERK, extracellular signal–regulated kinase; GPCR, G protein–coupled receptor; HIS, histidine; LTE_{4}, leukotriene E_{4}; LTD_{4}, leukotriene D_{4}; LT, leukotriene; MIP-1β, macrophage inflammatory protein 1β; mRNA, messenger RNA; P2Y, purinergic; PAS, periodic acid–Schiff; PG, prostaglandin; PTX, pertussis toxin; shRNA, short hairpin RNA.

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Abbreviations used: 2-MesAMP, 2-methylthioadenosine monophosphate; 5-LO, 5-lipoxygenase; ADP, adenosine diphosphate; AERD, aspirin-exacerbated respiratory disease; BAL, bronchoalveolar lavage; cDNA, complementary DNA; CHO, Chinese hamster ovary; COX, cyclooxygenase; Cys-LT, cysteiny LT; Der f, Dermatophagoides farinae; ERK, extracellular signal–regulated kinase; GPCR, G protein–coupled receptor; HIS, histidine; LTC_{4}, leukotriene C_{4}; LTD_{4}, leukotriene D_{4}; LT, leukotriene; MC, mast cell; MIP-1β, macrophage inflammatory protein 1β; mRNA, messenger RNA; P2Y, purinergic; PAS, periodic acid–Schiff; PG, prostaglandin; PTX, pertussis toxin; shRNA, short hairpin RNA.
in biological fluids. Consequently, LTE$_4$ levels can be monitored in the urine (Drazen et al., 1992), sputum (Lam et al., 1988), and exhaled breath condensate (Csoma et al., 2002) as an index of the cyst-LT synthetic pathway activity in human disease states such as asthma, where its concentrations can be markedly elevated.

To date, two G protein–coupled receptors (GPCRs) for cyst-LTs, termed type 1 and type 2 cyst-LT receptors (CysLT$_1$R and CysLT$_2$R), have been cloned and characterized (Lynch et al., 1999; Heise et al., 2000). These receptors share 38% amino acid identity. Each is 24–32% identical to the purinergic (P2Y) class of GPCRs that regulate cellular responses to extracellular nucleotides (Mellor et al., 2001), suggesting a phylogenetic relationship between these two GPCR classes. The human CysLT$_1$R, encoded by a gene on chromosome Xq21.13, is a high-affinity receptor for LTD$_4$ ($K_i$ ~1 nM; Lynch et al., 1999), whereas the human CysLT$_2$R is encoded by a gene on chromosome 13q14 and has equal affinity for LTC$_4$ and LTD$_4$ ($K_i$ ~10 nM; Heise et al., 2000). As neither receptor has significant affinity for LTE$_4$, the existence of an additional cyst-LT receptor with a preference for LTE$_4$ has long been suspected. Early studies demonstrated that purified LTE$_4$ is more potent than LTC$_4$ or LTD$_4$ for inducing contraction of guinea pig tracheal rings (Lee et al., 1984), whereas LTC$_4$ and LTD$_4$ were more potent on peripheral lung. Of the three cyst-LTs, only LTE$_4$ potentiates the contractile response of guinea pig trachea to histamine, a response which can be blocked by the administration of indomethacin, a nonselective inhibitor of the cyclooxygenase (COX) enzymes (Lee et al., 1984). LTE$_4$ inhalation by asthmatic individuals potentiates airway hyperresponsiveness to subsequent challenges with histamine. This potentiation is also blocked by oral administration of indomethacin (Christie et al., 1992a). Inhalation of LTE$_4$, but not of LTD$_4$, causes eosinophils, basophils, and MCs to accumulate in the bronchial mucosa of asthmatic individuals (Laitinen et al., 1993; Gauvreau et al., 2001). Patients with aspirin–exacerbated respiratory disease (AERD), a syndrome characterized by asthma, nasal polyps, and marked cyst-LT overproduction, exhibit selectively enhanced bronchoconstriction in response to LTE$_4$ relative to LTC$_4$ or to histamine when compared with aspirin-tolerant asthmatic individuals (Christie et al., 1993). Mice lacking both CysLT$_1$R and CysLT$_2$R ($Cysltr1^{-/-}$ $Cysltr2^{-/-}$ mice) exhibit enhanced skin swelling in response to intracutaneous LTE$_4$ relative to WT controls, indicating that a putative LTE$_4$-reactive GPCR (termed CysLT$_{3}$R) exists in the skin (Maekawa et al. 2008). Thus, the potency of LTE$_4$ as an inducer of inflammatory and physiological effects in vivo is not explained by the pharmacology of the classical GPCRs for cyst-LTs, which preferentially bind the metabolic precursors of LTE$_4$. Thus, the three cyst-LTs are all potent mediators, and show considerable tissue specificity for their respective actions. Both a 5-LO inhibitor (zileuton) and the drugs that block CysLT$_1$R (Knorr et al., 1998) show clinical efficacy in asthma, despite the negligible activity of LTE$_4$ at CysLT$_1$R and the fact that zileuton blocks only ~50% of cyst-LT generation in vivo (Israel et al., 1996; Liu et al., 1996). Identification of receptors and pathways through which LTE$_4$ exerts its effects may be highly significant in terms of the pathobiology of mucosal inflammation, as well as the treatment of asthma, AERD, and related diseases in which local concentrations of LTE$_4$ are elevated and/or end-organ reactivity to LTE$_4$ is high.

MCs respond strongly to cyst-LTs and are a useful cell type for modeling cyst-LT–induced signaling events and receptor functions. We previously demonstrated that human and mouse MCs express both CysLT$_1$R (Mellor et al., 2001) and CysLT$_2$R (Mellor et al. 2003) and that these receptors constitutively form heterodimers on this cell type (Jiang et al., 2007). Stimulation of MCs with LTD$_4$, the most potent agonist of the CysLT$_1$R, transactivates the kit tyrosine kinase (Jiang et al., 2006), induces calcium flux (Mellor et al., 2001), and phosphorylates extracellular signal-regulated kinase (ERK; Jiang et al., 2006). These signaling events amplify MC proliferation and induce their generation of cytokines and chemokines (Mellor et al., 2002). CysLT$_1$R is required for all of these LTD$_4$-induced responses, whereas CysLT$_2$R inhibits them (Jiang et al., 2007). MCs also express several P2Y receptors (Feng et al., 2004). We recently reported that LTE$_4$ induces ERK activation and COX-2 expression, and causes prostaglandin (PG) D$_2$ and macrophage inflammatory protein 1B (MIP-1B) generation by LAD2 cells, a well-differentiated human MC line (Kirshenbaum et al. 2003; Paruchuri et al., 2008), and to a lesser extent by primary cord blood–derived human MCs (hMCs). LTE$_4$-mediated production of PGD$_2$ by LAD2 cells was unaffected by short hairpin RNA (shRNA)–mediated knockdown of either CysLT$_1$R or CysLT$_2$R (Paruchuri et al., 2008), supporting the presence of a previously unrecognized LTE$_4$-reactive receptor on this cell type. A computer model (Nonaka et al., 2005) had predicted that the P2Y$_{12}$ receptor, an adenosine diphosphate (ADP)–reactive GPCR which is the target of the thienopyridine anti-thrombotic drugs (Foster et al., 2001), could be an LTE$_4$ receptor. In this study, we demonstrate a potent unique proinflammatory function for LTE$_4$ in the lung, and we demonstrate that P2Y$_{12}$ receptors are required for the functions of LTE$_4$ in vitro and in the lung in vivo. Our results suggest that P2Y$_{12}$ receptors may be a novel target for the treatment of asthma.

RESULTS

Recombinant human P2Y$_{12}$ receptors convey cellular responses to LTE$_4$

To determine if P2Y$_{12}$ receptors could mediate responses to LTE$_4$, we stably transfected Chinese hamster ovary (CHO) cells (which do not natively express classical CysLTRs [Maekawa et al., 2001] or P2Y$_{12}$ receptors) with constructs encoding the human P2Y$_{12}$ receptor protein in forward and reverse orientation. The transfectants were stimulated with exogenous LTC$_4$, LTD$_4$, or LTE$_4$. Fura-2 AM–loaded CHO cells expressing P2Y$_{12}$ receptors failed to flux calcium in response to LTE$_4$ but did exhibit a response to ADP, reflecting
failed to attenuate LTD₄- or LTE₄-mediated calcium flux in LAD2 cells (Fig. 2 A). We determined the effect of MK571 and 2-MesAMP on MIP-1β generation by LAD2 cells in response to stimulation for 6 h with LTD₄ and LTE₄, using IgE plus anti-IgE as a positive control. LTE₄ at doses of 100 and 500 nM induced the generation of large amounts of MIP-1β, exceeding the amounts generated in response to LTD₄ and to IgE plus anti-IgE (Fig. 2 B). Pretreatment of the LAD2 cells with 2-MesAMP blocked the LTE₄-mediated increment in MIP-1β production by >50% (Fig. 2 B). 2-MesAMP also reduced the response to the higher concentrations of LTD₄. MK571 suppressed the response to both ligands and was additive with 2-MesAMP for the suppression of the response to LTD₄. Neither antagonist altered the production of MIP-1β in response to IgE plus anti-IgE. To exclude potential off-target effects of the inhibitors, samples of LAD2 cells were transfected with lentiviruses encoding a P2Y₁₂ sequence-specific shRNA, a CysLT₁R-specific shRNA, or an empty vector control before stimulation. Knockdown of P2Y₁₂ receptors decreased the receptor messenger RNA (mRNA) expression by ~90% (Fig. 2 D) and did not alter expression of CysLT₁R or CysLT₂R proteins (not depicted). P2Y₁₂ receptor knockdown nearly abrogated MIP-1β production, completely eliminated PGD₂ production in response to LTE₄, and minimally affected the response to LTD₄. The knockdown of CysLT₁R completely blocked MIP-1β and PGD₂ production in response to LTD₄ and slightly (but not significantly) decreased the responses to LTE₄ (Fig. 2 C, bottom). Neither knockdown altered MIP-1β generation or PGD₂ production in response to IgE–anti-IgE (Fig. 2 C). LTE₄-mediated

**P2Y₁₂ receptor requirement for LTE₄-mediated activation and binding to LAD2 cells**

We had previously reported that LAD2 cells (a well-differentiated human MC sarcoma line; Kirshenbaum et al., 2003) exhibited activation responses to LTE₄ > LTD₄. To determine whether P2Y₁₂ receptors were responsible for these responses, Fura-2 AM–loaded LAD2 cells were stimulated with LTD₄ or LTE₄ in the presence or absence of 2-MesAMP or MK571. As reported previously (Paruchuri et al., 2008), MK571 blocked calcium responses of LAD2 cells to both ligands (unpublished data). In contrast, 2-MesAMP treatment

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**Figure 1. Activation by recombinant human P2Y₁₂ receptors in response to cys-LTs.** The human P2Y₁₂ receptor complementary DNA (cDNA) was cloned in forward and reverse orientation into the expression vector pEF1/His B and transfected into CHO cells using Fugene HD reagent. Stably expressing clones were selected using 1,000 µg/ml G418, and expression of the construct was confirmed by cytofluorographic detection of the polyhistidine (HIS) tag. (A) Calcium fluxes in CHO transfectants in response to 500 nM LTE₄, 500 nM LTD₄, and 100 µM ADP. Results in a second experiment were identical. (B) SDS-PAGE immunoblots showing phosphorylation of ERK2 by CHO cells stably expressing human P2Y₁₂ receptors in reverse (negative control) or forward orientations. Cells were stimulated with 100 µM ADP (positive control ligand), 500 nM LTD₄, or 500 nM LTE₄, for 15 min. The blots were stripped and reprobed with an antibody recognizing total ERK1 and ERK2. Dose responses are displayed in Fig. S1. (C) Effect of the selective P2Y₁₂ receptor antagonist 2-MesAMP (MeS) on ligand-induced ERK phosphorylation. P2Y₁₂ receptor-expressing CHO cells were stimulated with the same doses of agonists used in A, in the absence or presence of 100 µM 2-MesAMP. (D) Comparison of P2Y₁₂ receptor-mediated responses to cys-LTs with those of recombinant human CysLT₁R and CysLT₂R expressed in CHO cells, and the effect of 1 µM of the CysLT₁R antagonist MK571. Data in B–D are from individual experiments that were repeated at least three times with similar results.
To determine whether P2Y\textsubscript{12} receptors directly mediated LTE\textsubscript{4} binding, membranes were prepared from LAD2 cells with and without P2Y\textsubscript{12} knockdown. We first performed competitive radioligand binding assays using [\textsuperscript{3}H]ADP (the known natural ligand of P2Y\textsubscript{12} receptors) and unlabeled LTs as competitors. Unlabeled LTE\textsubscript{4} competed with labeled ADP, blocking 39 ± 9 and 50 ± 9\% of specific ADP binding at doses of 0.1 and 1 nM, respectively, and reaching a plateau (60 ± 7\%) at 1 \mu M (mean ± SEM for four separate experiments, as shown for one experiment [Fig. S3 A]). LTE\textsubscript{4} was more efficacious than LTD\textsubscript{4} (Fig. S3 B). Knockdown of P2Y\textsubscript{12} receptors reduced binding of [\textsuperscript{3}H]ADP by 40–60\% and completely eliminated competition by LTE\textsubscript{4} (Fig. S3, A and B, right). LAD2 cell membranes weakly bound [\textsuperscript{3}H]LTE\textsubscript{4} (converted from commercially prepared [\textsuperscript{3}H]LTD\textsubscript{4}; Fig. S3 C), but specific binding of [\textsuperscript{3}H]LTE\textsubscript{4} was not altered by the knockdown of P2Y\textsubscript{12} receptor (Fig. S3 C). To determine whether LTE\textsubscript{4} could block the ADP binding of P2Y\textsubscript{12} receptors expressed in isolation, the human forward and reverse P2Y\textsubscript{12} constructs were transiently expressed in COS-7 cells. The membranes from the transfectants expressing the forward construct bound \[^{38}P\]2-MesADP, a selective P2Y\textsubscript{12} receptor agonist. In contrast to ADP binding to LAD2 membranes, this binding was not competed by unlabeled LTE\textsubscript{4} or LTD\textsubscript{4} (Fig. S3 D). Additionally, these membranes failed to bind \[^{3}H\]LTE\textsubscript{4} (unpublished data).

**LTE\textsubscript{4} potentiates allergen-induced bronchial inflammation**

To determine whether LTE\textsubscript{4} could induce or potentiate histological signatures of pulmonary inflammation in mice, we determined the effect of 2.2 nmol of intranasal LTE\textsubscript{4} administered on three successive days on the lung histology of naïve BALB/c mice. We compared the effect to that of LTD\textsubscript{4}. The lungs of naïve BALB/c mice showed no evidence of cellular influx or goblet cell metaplasia after three doses of either cys-LT alone (unpublished data). Thus, we sought to determine whether either cys-LT amplified pulmonary inflammation induced by the inhalation of low-dose allergen in sensitized mice. 2 wk after sensitization with chicken egg OVA by i.p. injection, BALB/c mice received inhalation challenges on three consecutive days with low-dose OVA (0.1\%) for 30 min. 30 min before each challenge, the mice received 2.2 nmol of intranasal LTD\textsubscript{4}, LTE\textsubscript{4}, or a buffer control. A cohort of mice treated...
with 1% OVA were maintained as a positive control. The mice were then euthanized, their bronchoalveolar lavage (BAL) fluid was collected, and their lungs were examined histologically for evidence of inflammation and goblet cell metaplasia. Compared with saline-treated sensitized mice, mice challenged with low-dose OVA demonstrated low-grade BAL fluid eosinophilia (Fig. 3 A). The administration of LTD₄ did not increase BAL fluid eosinophilia (Fig. 3 A) and slightly potentiated both bronchovascular inflammation (Fig. 3, B and C) and goblet cell metaplasia (Fig. 3, D and E). In contrast, LTE₄ significantly enhanced BAL fluid eosinophilia (Fig. 3 A), inflammation (Fig. 3, B and C), and goblet cell metaplasia (Fig. 3, D and E). The extent of the cellularity and goblet cell responses of the LTE₄-treated animals approached the levels of these parameters in the mice treated with 1% OVA.

LTE₄-mediated pulmonary inflammation depends on P2Y₁₂ receptors and is independent of classical CysLT₁Rs

To determine whether P2Y₁₂ receptors accounted for the LTE₄-mediated augmentation of pulmonary inflammation, sensitized mice were treated with clopidogrel, an antithrombotic agent that is converted in vivo to an active metabolite that covalently binds to and irreversibly inactivates P2Y₁₂ receptors (Savi et al., 2006). Drug treatment began 2 d before the first administration of LTs to allow conversion of the prodrug. A separate cohort of sensitized mice was maintained without clopidogrel treatment as a control group. Both groups were challenged with low-dose OVA with or without additional LTE₄. Treatment with clopidogrel eliminated LTE₄-induced potentiation of both inflammation and goblet cell metaplasia (Fig. 4, A and B). To determine the effect of P2Y₁₂ receptor blockade on the induced expression of mRNAs encoding proteins involved in goblet cell metaplasia, real-time PCR was used to analyze the lungs of the mice for the expression of IL-13 and the goblet cell–associated glycoprotein MUC5AC. LTE₄ modestly increased the expression of both transcripts, whereas clopidogrel treatment substantially suppressed the expression of both (Fig. 4 C). There was no detectable induction of IL-4 or IL-5 transcripts (unpublished data).

Because pharmacologic antagonists can act in an off-target manner, we sought to determine the receptors required to mediate the effect of LTE₄ in the lungs of allergen-sensitized and -challenged mice using a molecular approach. First, we studied the ability of LTE₄ to amplify pulmonary inflammation in OVA-sensitized and -challenged C57BL/6 mice lacking P2Y₁₂ receptors (p2yr12−/− mice; Andre et al., 2003)
Figure 4. Role of P2Y12 receptors on potentiation of pulmonary inflammation by LTE4. (A) Bronchovascular inflammation (top) and goblet cell metaplasia in sensitized mice challenged with low-dose OVA with or without the prior administration of 2.2 nmol LTD4 or LTE4 30 min before each challenge. 500 µg/ml clopidogrel was added to the drinking water of the indicated groups of mice for 72 h before the first intranasal dose of LTs and was maintained throughout the treatment. Results are mean ± SEM from at least nine mice in each group. The experiments were repeated three times with similar results. (B) PAS stains (left) from representative mice in the indicated groups showing the effect of clopidogrel on goblet cell metaplasia. Higher magnification images of H&E stains (right) from the same animals showing cellular characteristics of the bronchovascular infiltrates. (C) Effect of clopidogrel administration on the steady-state expression of IL-13 and MUC5AC mRNA as determined by real-time PCR of whole lung RNA extracted 24 h after the last OVA challenge of the indicated groups. Data are mean ± SEM from four to five mice per group from a single experiment. Results in a second experiment were similar. (D–F) Male and female C57BL/6 p2ry12−/− mice and age- and sex-matched controls were sensitized and challenged with 0.1% aerosolized OVA on three consecutive days with or without intranasal LTE4 30 min before each challenge. (D) Total cell numbers (top), percentages of eosinophils (middle), and total numbers of eosinophils (bottom) in BAL fluid recovered 24 h after the last challenge with OVA. (E) Goblet cell metaplasia (top) and representative PAS stains (bottom) from WT and p2ry12−/− mice subjected to the same protocol. (F) Inflammation scores from the same mice. Data in D–F are from four mice per group. Results in a second experiment were similar. (G) BALB/c Cysltr1/Cysltr2−/− mice and age-matched WT controls were subjected to the same protocol as the p2ry12−/− mice. Total cell numbers (top), percentages of eosinophils (middle), and total numbers of eosinophils (bottom) in BAL fluid recovered 24 h after the last challenge with OVA. Results are from six mice per group. Three experiments were performed with similar results. (H) Goblet cell numbers (top) and representative PAS stains (bottom). (I) Quantitative assessment of bronchovascular inflammation as determined by H&E stain (top). Results are from six mice per group. Representative stains are shown (bottom). Error bars represent ± SEM. Bars, 100 µm.
along with age- and sex-matched C57BL/6 controls. Although cellular infiltration into the lung and BAL fluid was less pronounced in the C57BL/6 mice than in the BALB/c mice, LTE4 potentiated BAL fluid eosinophilia (Fig. 4 D), goblet cell metaplasia (Fig. 4 E), and bronchovascular infiltration (Fig. 4 F) in the WT controls, all of which were severely blunted in the p2ry12−/− mice (Fig. 4, D–F). To determine whether classical GPCRs for cys-LTs were also required for the LTE4 effects, BALB/c mice lacking both CysLT1R and CysLT2R (Cysltr1/Cysltr2−/− mice; Maekawa et al., 2008) were also studied. Because of limited numbers of available mice, all animals were sensitized and challenged with low-dose OVA, and half were treated with exogenous LTE4. Strikingly, the potentiation of OVA-induced BAL fluid eosinophilia (Fig. 4 G), goblet cell metaplasia (Fig. 4 H), and inflammation (Fig. 4 I) by LTE4 were completely intact in the Cysltr1/Cysltr2−/− mice, indicating that LTE4 was working independently of the known GPCRs for cys-LTs. Thus, the intrapulmonary actions of LTE4 in vivo require P2Y12 receptors but not classical cys-LT–reactive GPCRs.

Blockade of P2Y12 receptors blunts pulmonary inflammation induced by house dust mite antigen

To determine whether pharmacologic blockade of P2Y12 receptors altered pulmonary inflammatory responses in a more physiological model of pulmonary inflammation, C57BL/6 mice were administered an extract of house dust mite Dermatophagoides farinae (Der f) intranasally twice weekly for 3 wk, with or without clopidogrel treatment. Two different doses of Der f were used to elicit moderate (3 µg) and severe (10 µg) inflammation, respectively. At both antigen doses, the mice treated with clopidogrel showed ~75% attenuation of BAL fluid eosinophilia (unpublished data), as well as significant reductions in pulmonary inflammation, and goblet cell metaplasia compared with the cohort that did not receive clopidogrel (Fig. 5, A and B).

LTE4/P2Y12 receptor-mediated amplification of pulmonary inflammation requires platelets

Because P2Y12 receptors are essential for normal platelet activation in vivo (Andre et al., 2003), we sought to determine whether platelets were required for the response of sensitized challenged mice to exogenous LTE4. Platelets were depleted in sensitized BALB/c mice by the i.v. injection of a rat mAb against mouse CD42b (GPIb; Nieswandt et al., 2000) or an isotype-matched control IgG 48 h before to the first administration of LTD4 or LTE4. Treatment with the anti-CD42b antibody depleted platelets almost completely (99% depletion [unpublished data]) at the time of the first dose of LT. Platelet depletion resulted in a complete loss of the LTE4-mediated potentiation of airway eosinophilia, inflammation, and goblet cell metaplasia (Fig. 6, A and B). The effect of platelet depletion was identical to the effect of treatment of the mice with clopidogrel, and the two treatments were not additive (Fig. 6 B). Platelet depletion, like clopidogrel treatment, sharply reduced the LTE4-mediated expression of mRNA encoding IL-13.

Figure 5. Role of P2Y12 receptors in inflammation mediated by dust mite allergen. C57BL/6 mice were treated intranasally with the indicated dose of Der f extract twice weekly for 3 wk. Animals were euthanized 24 h after the last dose. (A) Effect of clopidogrel treatment on bronchovascular inflammation and goblet cell metaplasia in C57BL/6 mice subjected to intranasal challenge with the indicated doses of an extract from the house dust mite. Results are the mean ± SEM from five mice per group. The experiment was repeated three times with similar results. (B) Representative PAS stains of the lungs from mice in the indicated groups. Bar, 100 µm.
and MUC5AC (unpublished data). To determine whether LTE₄ alone induced platelet activation (leading to ADP release with potential resultant autocrine stimulation of P₂Y₁₂ receptors), human blood platelets were stimulated with 1 µM LTE₄ or with 100 µM ADP, and degranulation was assessed by cytofluorographic detection of P-selectin (CD62P). As expected, ADP elicited CD62P expression, but no CD62P expression was detected in response to stimulation with LTE₄ (Fig. 6 C).

**DISCUSSION**

This study establishes that P₂Y₁₂ receptors are essential for the actions of LTE₄, the only long-lived stable abundant member of the cys-LTs, in inflamed lung. Our findings help to explain long-recognized but unexplained properties of LTE₄ in airway biology. The involvement of cys-LTs in the pathobiology of asthma is established by the fact that 5-LO inhibitors (Israel et al., 1996; Liu et al., 1996) and CysLT₁R antagonists (Knorr et al., 1998) have clinical efficacy. The cloning and functional characterization of the CysLT₁R (Lynch et al., 1999) and CysLT₂R (Heise et al., 2000) explained the pharmacology of LTC₄ and LTD₄ predicted from studies of contractile tissues (Lee et al., 1984). The finding that neither GPCR showed significant binding or reactivity to LTE₄ was surprising given the plethora of data in human and animal studies that indicate the unique characteristics of this stable ligand relative to its short-lived precursors (Christie et al., 1992a, 1993; Laitinen et al., 1993; Gauvreau et al., 2001). Because we had previously demonstrated that LTE₄ could activate LAD2 cells by a mechanism independent of CysLT₁R and CysLT₂R (Paruchuri et al., 2008), and because LTE₄ was previously identified by an in silico model as a potential surrogate ligand for the P₂Y₁₂ receptor (Nonaka et al., 2005), we undertook this study to determine whether the P₂Y₁₂ receptor was a bona fide LTE₄-reactive receptor and to determine its contribution to LTE₄-induced proinflammatory events.

We first established that recombinant human P₂Y₁₂ receptor protein conveyed activation responses by CHO cells to LTE₄. Unlike most members of the P₂Y receptor class, native P₂Y₁₂ receptors do not couple to Gprotein or activate calcium flux; instead, they induce signaling through PTX-sensitive Goi2 proteins when stimulated with ADP (Foster et al. 2001; Lova et al., 2002; Woulfe et al., 2002). It was, thus, not surprising that CHO cells expressing P₂Y₁₂ receptors failed to flux calcium in response to cys-LTs (Fig. 1 A) or that blockade of P₂Y₁₂ receptors on LAD2 cells with 2-MesAMP failed to alter cys-LT–mediated calcium flux (Fig. 2 A), which was totally abrogated by MK571. However, heterologously expressed P₂Y₁₂ receptors responded to LTE₄ with PTX-sensitive ERK activation (Fig. 1). The dose range for this response (Fig. S1) is similar to the LTE₄ dose range required to compete with radiolabeled ADP for binding to LAD2 cell membranes (Fig. S3) and is consistent with that reported by Nonaka et al. (2005) using a P₂Y₁₂-Gai16 fusion protein to demonstrate calcium flux, also in CHO cells. The finding that cys-LT–induced ERK activation in the transfectants was resistant to MK571 (Fig. 1 D) implies that P₂Y₁₂ receptors could contribute to an element of cys-LT–driven pathobiology that is relatively selective for LTE₄ and may resist conventional CysLT₁R antagonists. This element may be especially relevant to pathological situations where LTE₄ is abundant as a result of its relative stability.

In our previous study, LTE₄ had exhibited unanticipated potency for inducing ERK activation and the generation of MIP-1β and COX–2-dependent PGD₂ by LAD2 cells (Paruchuri et al., 2008). Because both ERK and calcium-dependent transcriptional events are essential for MC activation, we sought to determine the potential contribution of P₂Y₁₂ receptors to the activation responses of LAD2 cells to LTE₄ and to contrast these responses to those elicited by LTD₄, the most potent CysLT₁R ligand. Although ineffective for blocking cys-LT–induced calcium flux, 2-MesAMP effectively

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**Figure 6.** Platelet dependence of the LTE₄ effect on bronchial inflammation and goblet cell metaplasia. Sensitized mice were treated i.v. with 50 µg (~2 µg/g body weight) of a monoclonal rat IgG directed against mouse CD42b (GPibx) or an equal amount of isotype control (both from Cemfret Analytics) 48 h before the first dose of LTE₄. Each antibody was diluted in 50 µl of sterile saline. The depletion of platelets was confirmed by automated counting, and some mice were treated with clopidogrel. (A) PAS stains of the lungs of representative mice treated with isotype control (top) or with an anti-CD42 platelet-depleting antibody (bottom). (B) Inflammation (top) and goblet cell metaplasia (bottom) in the lungs of mice treated with the indicated LT and antibody. A cohort of mice was treated with clopidogrel as indicated. Results in B are from a single experiment performed three times on different donors. Bars, 100 µm.
blocked the LTE₄-mediated increment in MIP-1β production (Fig. 2 B) and also reduced the response to the higher concentrations of LTD₄, indicating that LTD₄ at high concentrations can also activate native P2Y₁₂ receptors, as supported by its actions as an agonist for ERK activation in the P2Y₁₂ receptor transfectants (Fig. 1). MK571 suppressed MIP-1β generation in response to both ligands (likely reflecting the requirement for calcium flux for chemokine generation) and was additive with 2-MesAMP for the suppression of the response to LTD₄. The shRNA-mediated knockdowns of CysLT₁R and P2Y₁₂ receptors revealed strong dependence of LTD₄-mediated activation on CysLT₁R, whereas LTE₄-mediated responses were clearly P2Y₁₂ receptor dependent (Fig. 2 C). Although there is segregation of the receptor requirements for these two related ligands on the same cell, the ability of LTE₄ to “cross over” and induce some calcium signaling through the CysLT₁R may permit some complementarities between the CysLT₁R (via Gαq proteins and calcium-induced pathways) and P2Y₁₂ receptors (via Gαi proteins), particularly for chemokine generation. This is analogous to the cooperation by Gαq-linked P2Y₁ receptors with P2Y₁₂ receptors in regulating ADP responses of platelets (Lova et al., 2002; Woulfe et al., 2002). The P₂Y₁₂-dependent activation of LAD₂ cells does not likely reflect autocrine effects of released ADP because it was resistant to treatment of the cells with the ectonucleotidase apyrase (Fig. S2).

Surprisingly, although P2Y₁₂ receptors were essential for competition between LTE₄ with ADP for binding to membranes of LAD₂ cells (Fig. S3, A and B), they were not involved in the direct low-affinity binding of [3H]LTE₄ to these same membranes (Fig. S3 C). Additionally, LTE₄ could not compete for binding to P2Y₁₂ receptors expressed in isolation on COS-7 cells (Fig. S3 D). The fact that P2Y₁₂ receptors do not directly bind LTE₄ despite their essential nature implies that they are components of a complex with another LTE₄-reactive GPCR, perhaps with the putative CysLT₁R reported in the mouse skin (Maekawa et al., 2008). The facts that P2Y₁₂ receptors are required for LTE₄ to activate transfected CHO cells (Fig. 1) and LAD₂ cells (Fig. 2), and for competition between LTE₄ and ADP for binding to LAD₂ cells (Fig. S3 B), and that knockdown of P2Y₁₂ receptors did not reduce direct binding of radiolabeled LTE₄ (Fig. S3 C) are all consistent with this thesis. Precedents for such complexes on MCs include CysLT₁R and CysLT₂R heterodimers (Jiang et al., 2007) and a functional requirement of CysLT₁R for the uridine diphosphate-reactive P2Y₆ receptor (Jiang et al., 2009). Our data indicate that presence of P2Y₁₂ is required for signaling and activation by LTE₄ in a cell-specific context.

The fact that LTE₄, but not LTD₄, induces bronchial eosinophilia when administered by inhalation to the airways of individuals with asthma (Gauvreau et al., 2001) argued for the presence of an LTE₄-reactive receptor in inflamed lung. In our model, which was designed to study potentiation of submaximal bronchial inflammation in sensitized mice, we found that LTE₄ exceeded the potency of LTD₄ for potentiating BAL fluid eosinophilia (Fig. 3 A), cellular infiltration of the bronchovascular bundles (Fig. 3, B and C), and goblet cell metaplasia (Fig. 3, D and E). Thus, LTE₄ exceeds the efficacy of LTD₄ for potentiating bronchial inflammation in both mouse and man, a pattern not explicable by the known properties of CysLT₁R or CysLT₂R. Several pieces of evidence link these LTE₄-mediated responses in mice to the P2Y₁₂ receptor. First, treatment of the mice with a highly potent selective antagonist of the P2Y₁₂ receptor, clopidogrel, completely eliminated the histological response to LTE₄ (Fig. 4, A and B), which is associated with blockade of LTE₄-potentiated expression of IL-13, the Th2 cytokine most closely linked to the development of goblet cell metaplasia (Zhu et al., 1999), and of MUC5AC, a major mucus glycoprotein which is controlled by IL-13 (Fig. 4 C). Second, LTE₄ fully amplified pulmonary inflammation in Cysltr1/ Cysltr2−/− mice (Fig. 4, G–I). Lastly, the ability of LTE₄ to potentiate mucosal inflammation and goblet cell metaplasia was nearly completely abrogated in the absence of P2Y₁₂ receptors (Fig. 4, D–F). Thus, LTE₄ requires P2Y₁₂ receptors, but not the classical CysLTRs, to amplify the histological signatures of allergen-induced pulmonary inflammation. Because LTD₄ is converted in vivo to LTE₄, it was somewhat surprising that the ligands do not behave interchangeably in potentiating bronchial eosinophilia in mouse or man. In addition to P2Y₁₂-dependent effects of LTE₄, LTD₄ may initiate inhibitory signals through CysLT₂R (Jiang et al., 2007) or other yet-to-be-identified GPCRs that recognize LTD₄ but not LTE₄. The effects of clopidogrel in the model of airway disease induced by the natural allergen Der f without the use of exogenous LTE₄ (Fig. 5) support the importance of the P2Y₁₂ pathway in the integrated biology of pulmonary inflammation (although this does not discriminate between effects mediated by LTE₄ from ADP). The blockade of the response by clopidogrel distinguishes the P2Y₁₂ receptor-dependent response of the lung to LTE₄ from the clopidogrel-resistant LTE₄ response in the skin (Maekawa et al., 2008). Thus, it is likely that different receptors or receptor complexes mediate response to the stable ligand LTE₄ in distinct anatomical distributions.

Platelets accumulate in the lungs of individuals with asthma (Jeffery et al., 1989) and also are recruited to the lungs of OVA-sensitized and -challenged mice by an IgE-dependent mechanism (Pitchford et al., 2008). Activated platelets generate mediators (serotonin and thromboxane) that can potentiate airway inflammation. The essential nature of P2Y₁₂ receptors for normal platelet function (Andre et al., 2003) led us to examine the effect of platelet depletion on the response of sensitized challenged mice to exogenous LTE₄. Indeed, the response to LTE₄ was totally abrogated by platelet depletion (Fig. 6, A and B). Whether the requirement for platelets is direct or indirect is less clear. The fact that LTE₄ did not induce platelet expression of CD62P (an activation marker used as a surrogate for ADP release; Abrams and Shattil, 1991; Fig. 6 C) argues that LTE₄ does not trigger an ADP-dependent autocrine loop initiated by LTE₄-mediated activation of another
Because platelet activation involves complementary signaling in both Gi and Gq protein–mediated pathways (Jin et al., 2002; Lova et al., 2002; Woulfe et al., 2002) and P2Y12 provides only the Gi-linked component, LTE4 (and P2Y12) likely synergizes in vivo with a second agonist to facilitate platelet functions in the lung. It is noteworthy that LTE4–mediated potentiation of the contractile responses of both guinea pig and human airway smooth muscle is COX dependent (Christie et al., 1992a) and was attributed to secondary generation of thromboxane, a major platelet-derived eicosanoid (Jacques et al., 1991). In retrospect, this finding may have reflected P2Y12 receptor–dependent signaling on platelets or other cell types. The fact that LTE4–potentiating inflammation only in sensitized challenged mice may reflect the previously described platelet–mediated pathway for leukocyte recruitment that depends on sensitization and IgE (Pitchford et al., 2008). The complete lack of LTE4 reactivity in the face of platelet depletion argues against a role for MCs and other P2Y12–bearing cell types, at least in this model.

Our findings suggest a potential therapeutic application for P2Y12 receptor antagonists that may be especially relevant to AERD, which is associated with both high levels of LTE4 in the urine (Christie et al., 1992b) and selective hypersensitivity to LTE4 (Christie et al., 1993). In AERD, both 5-LO antagonists and CysLT1R antagonists provide disease control and attenuate the consequences of aspirin challenge (Israel et al., 1993; Dahlem et al., 1998, 2002; White et al., 2006), in which the reaction is characterized by a marked surge in LTE4 generation. The fact that the effects of LTE4 persist in the absence of CysLT1R and CysLT2R implies that this pathway would be resistant to the available cys-LT receptor antagonists, all of which selectively block CysLT1R. We speculate that simultaneous interference with the bronchoconstrictive effects of LTD4 (via CysLT1R) and with proinflammatory effects of LTE4 (by P2Y12), or more complete blockade of 5-LO, might improve clinical efficacy. Our study furthermore highlights the biological significance of the structural and functional relationships between the P2Y and cys-LT–reactive classes of GPCRs.

MATERIALS AND METHODS

Animals. All animal protocols were approved by the Dana Farber Cancer Institute Animal Care and Utilization Committee. BALB/c mice lacking both CysLT1R and CysLT2R (Cysltr1−/− Cysltr2−/− mice) and their WT littermate controls were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Andre et al., 2003) on a mixed C57BL/6-129 background and backcrossed for 10 generations with C57BL/6 mice. WT BALB/c and C57BL/6 mice were purchased from Taconic. Backcrossing for 10 generations with C57BL/6 mice. WT BALB/c and C57BL/6 mice were purchased from Taconic. Balb/c mice were purchased from Taconic. Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacking P2Y12 receptors (p2y12−/− mice) were derived as described elsewhere (Maekawa et al., 2008). Mice lacki...
were evaluated. The stained goblet cells were enumerated in at least four in-

Statistics. Data are expressed as mean ± SEM from at least three experi-

Online supplemental material. Fig. S1 shows the dose-dependent effects of

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The stained goblet cells were enumerated in at least four in-

dependent bronchovascular bundles from the lung sections obtained for each animal in the different experimental groups. The length of basal lamina of corresponding bronchus was measured by ImageJ image analysis software (National Institutes of Health). Only the comparable large-caliber pretermi-
nal bronchi (diameter 200–220 µm) were examined because minimal changes occur in terminal bronchioles. The data were expressed as the mean of gob-

let cell counts stained in each bronchus in each section per millimeter of bronchial basal lamina.

0.1% Tween-20 (1:1,000) overnight at 4°C on shaker and then with secondary antiboby (peroxidase-conjugated anti-rabbit or anti-mouse). Bands were visualized with enhanced chemiluminescence (Thermo Fisher Scientific).

Binding assays. [3H] LTD4 ([14,15,19,20-3H(N)]; specific activity 100–240 Ci/mmol; PerkinElmer) was converted to [3H]LTE4 by the dipeptidases present in the serum. In brief, 100 µl (80 nM) [3H]LTD4 was incubated with 100 µl of 10% serum for 2 h at room temperature. The converted product was extracted into 400 µl of methanol, evaporated in the presence of nitrogen, and diluted to the required concentration with the binding buffer for the binding assay. The conversion was confirmed by running an aliquot on high-performance reverse-phase liquid chromatography. The fraction elut-
ing with the LTE4 peak accounted for >99% of the radioactivity used in the assays. The specific activity of the resultant LTE4 was consistently 80–100% that of the LTD4 from which it was converted. [3H]ADP and [3H]LTE4 binding assays were performed using membrane proteins as described earlier (Maekawa et al., 2001). In brief, cells were washed in PBS, resuspended in PBS supplemented with protease inhibitor cocktail, and lysed by sonication for 5 min. The lysed cells were centrifuged at 100,000 g for 45 min and the microsomal pellet was resuspended in 1 ml PBS. Protein concentration was determined using a Protein Assay kit (Bio-Rad Laboratories). 50 µg of mem-

bicronial rat IgG directed against mouse CD42b (both from Emfret Analytics; Bain for her assistance with the binding assays.

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