Review
Allergy Asthma Immunol Res. 2014 July;6(4):288-295.
http://dx.doi.org/10.4168/aair.2014.6.4.288
pISSN 2092-7355 • eISSN 2092-7363

AAIR
Allergy, Asthma & Immunology Research

Cysteinyl Leukotrienes and Their Receptors; Emerging Concepts

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Cysteinyl leukotrienes (cys-LTs) are potent mediators of inflammation derived from arachidonic acid through the 5-lipoxygenase/leukotriene C_4 synthase pathway. The derivation of their chemical structures and identification of their pharmacologic properties predated the cloning of their classical receptors and the development of drugs that modify their synthesis and actions. Recent studies have revealed unanticipated insights into the regulation of cys-LT synthesis, the function of the cys-LTs in innate and adaptive immunity and human disease, and the identification of a new receptor for the cys-LTs. This review highlights these studies and summarizes their potential pathobiologic and therapeutic implications.

Key Words: Leukotrienes; 5-lipoxygenase; asthma; AERD

INTRODUCTION

Leukotrienes are lipid mediators generated from arachidonic acid through the 5-lipoxygenase (5-LO) pathway. They are named for their cells of origin (leukocytes) and the presence of three positionally conserved double bonds (trienes). The 2 classes of leukotrienes, cysteinyl leukotrienes (cys-LTs) and leukotriene B_4 (LTB_4), have broad array of bioactivities and cellular targets. Both 5-LO inhibitors and cys-LT receptor antagonists are useful for the treatment of asthma and rhinitis.[1-3] Recently studies using molecular approaches have demonstrated that cys-LTs possess multiple cell targets and immunologic functions, and act through a receptor system far more complex than previously anticipated. This review highlights these recent studies, and will consider their potential pathobiologic and therapeutic implications.

Regulation of leukotriene synthesis

Leukotriene synthesis is initiated during the activation of leukocytes, when arachidonic acid is liberated from the membrane phospholipids by a cytosolic phospholipase A_2.[4] 5-LO activating protein presents arachidonic acid to 5-LO, which catalyzes the formation of 5-hydroperoxyeicosatetraenoic acid and then the unstable epoxide LTA_4.[5] In mast cells, macrophages, eosinophils, and basophils, LTC_4 synthase (LTC_4S) conjugates LTA_4 to reduced glutathione, forming LTC_4, the parent of the cys-LTs.[6] Once formed, LTC_4 is transported to extracellular space via the ATP-binding cassette (ABC) transporters-1 and-4 and then metabolized to LTD_4 and LTE_4 by γ-glutamyl transpeptidases and dipeptidases, respectively. The rapid extracellular metabolism of LTC_4 and LTD_4 results in short biologic half-lives relative to the stable mediator LTE_4, which is abundant and readily detected in biologic fluids. In neutrophils, LTA_4 is hydrolyzed by a cytosolic LTA_4 hydrolase enzyme to form LTB_4, a dihydroxy leukotriene that is a potent chemoattractant for neutrophils and monocytes.[7]

5-LO activity is substantially upregulated when granulocytes are exposed ex vivo to hematopoietic cytokines such as GM-CSF or (in the case of eosinophils) IL-5.[8-11] In cord blood-derived human mast cells, IL-3 and IL-5 enhance the function of 5-LO by inducing its import from the cytosol to the nucleoplasm, whereas IL-4 potently induces expression and function of LTC_4S.[12] LTC_4S enzymatic function can be inhibited by protein kinase C (PKC)-dependent phosphorylation, which can limit the generation of cys-LTs *ex vivo*.[13] 5-LO activity is suppressed by stimuli that induce cyclic adenosine monophosphate (cAMP) accumulation, leading to serine phosphorylation of 5-LO by cAMP-dependent protein kinase A (PKA).[11] These *in vitro* studies suggest that LT production is tightly regulated by

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Received: December 3, 2013; Accepted: January 2, 2014
• There are no financial or other issues that might lead to conflict of interest.

the microenvironment and intracellular phosphorylation events, with mechanisms that can respectively enhance and limit the expression and function of the critical metabolic enzymes dependent on context.

Cysteinyl leukotriene receptors

Early pharmacologic profiling studies predicted the existence of at least 2 cys-LT receptors in mammalian tissues.[14] The molecular characterization of the classical G protein-coupled receptors (GPCRs) partially reconciled this pharmacology. The type 1 cys-LT receptor, CysLT$_1$R, is a high-affinity receptor for LTD_4 and the target of antagonists (Montelukast, Zafirlukast, and Pranlukast) that are used for the management of asthma. The cloned human CysLT$_1$R gene encodes a GPCR of 339 amino acids.[15] Human CysLT$_1$R mRNA is expressed in bronchial smooth muscle and substantially in myeloid cells, such as macrophages and mast cells. The human CysLT$_2$R is 38% identical to CysLT$_1$R in amino acid sequence.[16] CysLT$_2$R binds LTC_4 and LTD_4 with equal affinity, and binds LTD_4 with affinity one-log less than CysLT$_1$R. CysLT$_2$R is resistant to Montelukast, and is expressed both on cells that also express CysLT$_1$R (*e.g.*, myeloid cells, smooth muscle), as well as endothelial cells, cardiac Purkinje cells, adrenal medulla, and brain.[16] The incompletely overlapping distribution of the 2 classical receptors for cys-LTs suggests that they have both complementary and distinct functions.

In contrast to their affinities for LTC_4 and LTD_4, the cloned CysLT$_1$R and CysLT$_2$R receptors display trivial binding affinity for the stable metabolite LTE_4. Nonetheless, studies of human tracheal explants and guinea pig tracheal rings had predicted the existence of a third cys-LT receptor with a preference for LTE_4.[14,17] LTE_4 also was equipotent to its precursors for inducing wheal and flare responses when injected intradermally into humans.[18] Recently GPR99, previously reported as an oxyglutarate receptor,[19] was identified as a potential LTE_4 receptor.[20] LTE_4 binds and activates GPR99 at low nM range concentrations in transfected cells, and resists blockade by MK571, a prototype CysLT$_1$R antagonist. The ability of LTE_4 to induce cutaneous vascular permeability in mice depends largely on the presence of GPR99. GPR99 mRNA is expressed strongly by kidney and smooth muscle. Precise definition of its cellular distribution awaits the development of suitable antibody reagents, and its role in allergic inflammation is to be determined.

Regulation of cysteinyl leukotriene receptor function

As is the case for the cys-LT synthesis, cellular responsiveness to cys-LTs can be modulated both by exogenous stimuli and intracellular phosphorylation events. IL-4 and IL-13 upregulate the expression and function of CysLT$_1$R by human peripheral blood monocytes and monocyte-derived macrophages.[21] IL-13, but not IL-4, upregulates CysLT$_2$R expression as well in human monocytes.[22] IL-13 and transforming growth factor beta induce CysLT$_1$R expression by human bronchial smooth muscle cells.[23] CysLT$_1$R can be inducibly expressed by mouse T cells stimulated through the T cell receptor.[24] CysLT$_1$R signaling is also controlled by PKA[25] - or PKC[26] -dependent phosphorylation and desensitization. PKC mediates ligand-induced internalization of CysLT$_1$R following stimulation with LTD_4.[27] PKC activation by members of the purinergic (P2Y) family of GPCRs, which are homologous to the cys-LT receptors, can induce heterologous, PKC-dependent phosphorylation and desensitization of CysLT$_1$R without causing its internalization.[26] Since nucleotides, the natural ligands for P2Y receptors, are released in large quantities during acute inflammatory responses,[28] signaling through the cognate P2Y receptors may limit potentially deleterious effects of CysLT$_1$R signaling in cells that express both classes of receptors (Figure). Moreover, the overlap in the cytokines (IL-4) and protein kinases (PKA, PKC) that respectively enhance and suppress the functions of the synthetic and receptor systems suggest that cys-LT production may be regulated in parallel with end-organ responsiveness.

CysLT$_1$R functions can also be regulated by direct physical interactions with other GPCRs. CysLT$_1$R and CysLT$_2$R heterodimerize in cultured human mast cells.[29] The presence of CysLT$_2$R limits the levels of membrane expression of CysLT$_1$R, and dampens the capacity of CysLT$_1$R to induce phosphorylation of extracellular signal regulated kinase and proliferation in this cell type. GPR17, a GPCR homologous to CysLT$_1$R and CysLT$_2$R,[30] was originally "deorphanized" as a dual-specific receptor for cys-LTs and uracil nucleotides.[31] However, we and others could not reproduce GPR17 activation by either ligand type in various assay systems.[30,32,33] Instead, GPR17 functions as a negative regulator of LTD_4-mediated CysLT$_1$R activation, and markedly reduces binding of LTD_4 when the two receptors are co-expressed in cell lines.[30] Accordingly, mice lacking GPR17 (*Gpr17 −/−* mice) showed markedly enhanced CysLT$_1$R-dependent tis-

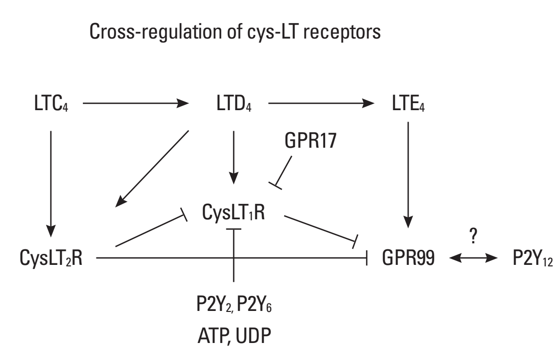

Figure. Cross-regulation of the cysteinyl leukotriene receptors. CysLT$_1$R function is inhibited both by direct physical interactions with CysLT$_2$R or GPR17, and by heterologous, PKC-dependent phosphorylation by P2Y receptors. The lack of both CysLT$_1$R and CysLT$_2$R amplifies cutaneous responses to LTE_4, suggesting that both classical receptors cross-regulate GPR99. The requirement for P2Y$_{12}$ receptors for the ability of LTE_4 to amplify pulmonary eosinophilia could reflect an interaction with GPR99.

sue edema induced by IgE-dependent passive cutaneous anaphylaxis.[30] Thus, at least two GPCRs ($CysLT_2R$ and GPR17) dampen $CysLT_1R$ function by direct physical interactions. The fact that both direct and indirect mechanisms can limit signaling through $CysLT_1R$ (Figure) implies that such limitation is critical for homeostasis of immune and inflammatory responses.

Cys-LTs in human allergic disease

Asthma and rhinitis

Based on their potencies as airway smooth muscle spasmogens and inducers of vascular leak, cys-LTs were considered potential pathogenetic mediators of asthma and rhinitis decades before the cloning of the cys-LT receptors. When administered by inhalation to asthmatic and nonasthmatic human subjects, both LTC_4 and LTD_4 induced bronchoconstriction at doses several log-fold lower than histamine.[34-36] LTE_4 was a weaker bronchoconstrictor than LTC_4 and LTD_4, but was ~1-log-fold more potent in inducing bronchoconstriction in asthmatic subjects relative to nonasthmatic controls.[37] Additionally, when delivered by inhalation, LTE_4 caused the accumulation of eosinophils and basophils in the bronchial submucosa of mild asthmatic subjects, whereas LTD_4 did not.[38] In retrospect, these findings not only implied that end-organ reactivity to LTE_4 is specifically enhanced in asthma, but also suggested the existence of distinct receptors with a preference for binding and activation by LTE_4.

Cys-LT production increases substantially in association with allergic inflammation and asthma, likely reflecting the activation of mast cells and eosinophils in the lesional tissues.[39] Unfractionated leukocytes from subjects with asthma generate several fold higher levels of both LTB_4 and LTC_4 than do leukocytes from the blood of nonasthmatic controls in response to stimulation with calcium ionophore.[40] Urinary levels of LTE_4 increase during spontaneous asthma exacerbations,[41] and correlate with decline in FEV1.[42] Treatments with either zileuton, a 5-LO inhibitor,[43] or with antagonists of $CysLT_1R$[44] each reduce the frequency of asthma exacerbations. Intravenous Montelukast increases peak expiratory flow rates in adult asthmatic subjects presenting to the emergency department with airflow obstruction compared with placebo.[45] These findings suggest that cys-LTs contribute substantially to exacerbations of asthma. $CysLT_1R$ antagonists also attenuate the magnitude of decline in FEV_1 in response to allergen challenge.[46] Cys-LT-generating enzymes are expressed by eosinophils, monocytes, and mast cells in nasal biopsies from subjects with allergic rhinitis,[39] and $CysLT_1R$ and $CysLT_2R$ localize to both hematopoietic and non-hematopoietic cell types in the nasal tissue.[39,47] Additionally, $CysLT_1R$ is expressed by human Th2 cells in peripheral blood from atopic subjects.[48] Montelukast, alone or in combination with an H_1 histamine receptor antagonist, is superior to placebo for reducing nasal congestion in the treatment of seasonal allergic rhinitis.[3] The effects of $CysLT_1R$ antagonists on rhinitis may reflect the actions of the cys-LTs on the vasculature as well as resident inflammatory cells.

AERD

AERD is characterized by adult onset asthma, severe rhinosinusitis with nasal polyps, and idiosyncratic respiratory reactions to aspirin and other nonselective inhibitors of cyclooxygenase (COX).[49] Baseline levels of urinary LTE_4 in subjects with AERD exceed the levels seen in aspirin tolerant asthmatic controls by several fold, and increase further and markedly in response to provocative challenge with aspirin.[50] The administration of either Zileuton or $CysLT_1R$ antagonists attenuates the severity of aspirin-induced bronchoconstriction in AERD.[51] Both classes of drugs were also superior to placebo for improving sinonasal function.[2,52] Thus, cys-LTs are involved in both the upper and lower respiratory tract pathology typical of AERD.

Eosinophils are the most abundant effector cell in bronchial and nasal biopsies from patients with AERD, and show over-expression of LTC_4S protein relative to eosinophils in biopsies from aspirin tolerant controls.[53,54] Platelets, which lack 5-LO, also express LTC_4S and can convert granulocyte-derived LTA_4 to LTC_4 through a transcellular mechanism.[55] In the blood and nasal polyps from patients with AERD, eosinophils, monocytes, and neutrophils display markedly increased numbers of adherent platelets compared to samples from aspirin tolerant controls.[56] These adherent platelets contribute as much as 60% of the LTC_4S activity associated with peripheral blood granulocytes obtained from subjects with AERD, and the percentages of blood granulocytes that are platelet-adherent correlated strongly with the levels of urinary LTE_4.[56] Mast cell activation accompanies the responses to aspirin challenge in AERD,[57] and the administration of mast cell stabilizing cromone drugs blocks the rise in urinary LTE_4 that accompanies reactions.[58] Collectively, these studies suggest that the dysregulation of cys-LT production in AERD reflects several cell types. Recently developed models of AERD in mice (see below) may more precisely define the cellular and molecular mechanisms responsible for dysregulated cys-LT production in AERD.

In addition to dysregulated cys-LT generation, subjects with AERD show enhanced end-organ reactivity to cys-LTs. Compared with aspirin tolerant asthmatic controls, individuals with AERD demonstrate bronchoconstriction in response to inhaled LTE_4[59] and LTD_4[60] at significantly lower doses. The numbers and percentages of $CysLT_1R$-positive mast cells, eosinophils, and monocytes in nasal biopsies from patients with AERD exceed those observed in the tissues of aspirin-tolerant asthmatic controls.[47,61] $CysLT_1R$ expression on hematopoietic cells decreases following desensitization to aspirin,[61] a procedure that attenuates bronchial reactivity to LTE_4.[62] The numbers and distributions of $CysLT_2R$-positive cells do not differ between aspirin tolerant asthmatics and subjects with AERD. Interestingly, bronchial reactivity to inhaled LTD_4 in AERD or aspirin tolerant

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asthma does not correlate with the numbers of $CysLT_1R$- or $CysLT_2R$- expressing cells in bronchial biopsies.[60] It is tempting to speculate that non-classical receptors, such as GPR99, may account for a component of the end organ responsiveness to cys-LTs (particularly to LTE_4) observed in AERD.

Understanding functions of the cys-LTs and their receptors in mice

The development of mice lacking LTC4S (*Ltc4s–/–*), $CysLT_1R$ (*Cysltr1–/–*), $CysLT_2R$ (*Cysltr2–/–*), and both receptors (*Cysltr1/Cysltr2–/–*) has permitted in-depth studies of the role of cys-LTs in immune and inflammatory responses. These studies have revealed complex and, in some instances, unanticipated functions for cys-LTs and their receptors in a variety of biologic responses detailed below.

Vascular leak

In a mast cell and IgE-dependent model of passive cutaneous anaphylaxis, *Ltc4s–/–* mice displayed reductions in ear skin swelling of ~50% compared to wild-type (WT) mice .[63] Intraperitoneal injections of zymosan, a yeast cell wall glycan that elicits LTC_4 generation from macrophages, induced vascular leak that was reduced in both the *Ltc4s–/–* and *Cysltr1–/–* strains by ~50% compared with WT controls.[63,64] The responses of *Cysltr2–/–* mice were equivalent to those of WT controls. Thus, $CysLT_1R$ plays a key role in mediating vascular leak in models where cys-LTs are generated in response to antigen- or pathogen-dependent stimuli.

To determine whether additional cys-LT receptors participated in vascular leak, we subjected *Cysltr1/Cysltr2–/–* mice to direct intracutaneous challenges with cys-LTs. Surprisingly, LTC_4 and LTD_4 induced tissue edema in *Cysltr1/Cysltr2–/–* mice that was comparable to WT mice, and LTE_4 induced marked tissue edema in this strain, with 64-fold enhanced sensitivity to LTE_4 over the WT controls. This enhanced response to LTE_4 was inhibited by pretreatment of the mice with pertussis toxin and a Rho kinase inhibitor, suggesting that it was mediated by a previously unrecognized G protein-coupled cys-LT receptor with a preference to LTE_4.[65] Given that GPR99 bound LTE_4 in transfected cells, we generated *Gpr99–/–* and *Gpr99/Cysltr1/Cysltr2–/–* mice for comparison with WT and *Cysltr1/Cysltr2–/–* mice. GPR99 deletion from the *Cysltr1/Cysltr2–/–* mice eliminated the vascular leak in response to the cys-LT ligands, indicating that GPR99 is likely to be a true cys-LT receptor. Furthermore, the *Gpr99–/–* mice showed a dose-dependent loss of LTE_4-mediated vascular permeability, but not to LTC_4 or LTD4, suggesting a preference of GPR99 for LTE_4.[20]

Th2 Immunity

Lung Th2 immunity to the house dust mite *Dermatophagoides farinae (Df)* requires stimulation of the myeloid C-type lectin receptor, Dectin-2.[66,67] Based on a protocol of sensitization of naive WT mice by means of adoptive transfer of *Df*-pulsed dendritic cells (DCs), Th2 responses to *Df* require the expressions of LTC_4S and $CysLT_1R$ by DCs. Interestingly, both *Cysltr2–/–* mice and *Gpr17–/–* mice showed markedly augmented eosinophilic pulmonary inflammation, serum IgE, and Th2 cytokine generation in response to *Df* sensitization and challenge compared to WT controls.[18] *Df*-pulsed DCs derived from *Cysltr2–/–* mice and *Gpr17–/–* mice induce an enhanced pulmonary eosinophilic and Th2 immune response in WT mice when compared with WT DCs. The enhanced response induced by *Gpr17–/–* DCs was eliminated by introduction of the *Cysltr1–/–* allele,[68] whereas the introduction of the *Ltc4s–/–* allele eliminated the potentiation of Th2 immunity induced by transfer of *Cysltr2–/–* DCs.[69] Thus, constitutive downregulation of $CysLT_1R$ function by GPR17 and $CysLT_2R$ may be critical to maintain homeostasis during the induction of Th2 immunity, at least to allergens (and potentially microbes) that bear ligands for Dectin-2.

Activation of innate lymphoid cells

Type 2 innate lymphoid cells (ILC2) are innate lymphocytes that release large quantities of IL-5 and IL-13 when activated by cytokines, such as IL-33, IL-25, or thymic stromal lymphopoietin (TSLP), derived from epithelial cells.[70] A recent study implicated the cys-LTs in the activation of ILC2 cells. Intrapulmonary challenge of mice with an extract from the mold *Alternaria alternata* strongly induced the generation of cys-LTs in the lung, and the recruitment and activation of ILC2.[71] ILC2 expressed $CysLT_1R$, and responded to stimulation in vitro and in vivo with LTD_4 by proliferating and releasing cytokines. Interestingly, while both LTD_4 and IL-33 caused lung ILC2 to generate IL-5 and IL-13, only LTD_4 caused them to generate IL-4. Ex vivo stimulation of lung ILC2 with either LTD_4 or LTE_4 caused the production of IL-5. While the IL-5 production in response to LTD_4 could be blocked by Montelukast, LTE_4-induced IL-5 production was resistant to Montelukast. This study suggests that cys-LTs can contribute to Th2 immunity through direct actions at ILC2. These effects reflect cys-LT actions both classical and nonclassical receptors that can induce effector cytokine production.

Platelet-dependent pulmonary eosinophilia

Platelets are essential for the development of pulmonary eosinophilia and airway remodeling in mouse models of ovalbumin (OVA) sensitization and challenge.[72,73] Activated platelets express P-selectin, which permits their adherence to leukocytes and primes leukocytes for directed migration via integrins. Mouse and human platelets express both $CysLT_1R$ and $CysLT_2R$,[74,75] as well as the $P2Y_{12}$ receptor, a homologue of the cys-LT receptors that binds ADP. Stimulation of mouse platelets with LTC_4 strongly induces their expression of P-selectin in an entirely $CysLT_2R$-dependent manner, while LTD_4 or LTE_4 are inactive. Intratracheal administration of LTC_4, but not LTD_4, markedly amplifies the recruitment of eosinophils to the airways of sensitized mice challenged with low-dose OVA. This amplification requires platelets, and is attenuated in *Cysltr2–/–* mice, suggesting a direct stimulatory effect of LTC_4 on platelet-associated $CysLT_2R$ in the lung vasculature.

Although LTE_4 fails to directly activate mouse or human platelets *in vitro*,[75,76] intratracheal administration of LTE_4, like that of LTC_4, potentiates OVA-induced eosinophilia in a platelet-dependent manner in WT mice.[76] In this model, LTE_4 is fully active in *Cysltr1/Cysltr2–/–* mice, suggesting that it acts at a non-classical cys-LT receptor. Both the effects of LTE_4 (*in vivo*) and of LTC_4 (*in vivo* and *in vitro*) depend exquisitely on the $P2Y_{12}$ receptor.[75,76] A computer modeling study predicted that $P2Y_{12}$ receptors might recognize LTE_4 as a surrogate ligand,[77] and LTE_4 elicits calcium flux[77] and phosphorylation of extracellular signal regulated kinase[76] in transfected cells over-expressing human $P2Y_{12}$ receptors. Nonetheless, radiolabeled LTE_4 does not directly bind to microsomal membranes from $P2Y_{12}$ receptor-expressing transfectants. It is presently unknown whether the involvement of $P2Y_{12}$ in LTE_4-dependent signaling responses and airway inflammation reflects a direct interaction between $P2Y_{12}$ receptors and a bona fide LTE_4 receptor, such as GPR99. The therapeutic potential of drugs that block $P2Y_{12}$ receptors in asthma or AERD is unexplored.

AERD-like models

Although several cellular abnormalities in eicosanoid synthesis and receptor function have been described in AERD,[49] the lack of a valid model of the disease has restrained progress in defining the key pathogenetic steps. Hirata *et al.* generated a transgenic mouse strain over expressing LTC_4S and examined the phenotype in OVA-induced pulmonary inflammation with or without treatment with a COX inhibitor, sulpyrine.[78] OVA-challenged LTC_4S-transgenic mice, but not similarly treated WT mice, demonstrated a significant increase in airway resistance by sulpyrine treatment. This is associated with increases in LTC_4 and LTB_4 in bronchoalveolar lavage (BAL) fluid in sulpyrine-treated OVA-challenged transgenic mice. Importantly, the increase in airway resistance was inhibited by Pranlukast, a $CysLT_1R$ antagonist. This study demonstrates that the pathognomonic feature of aspirin-induced bronchoconstriction can be reproduced in a mouse model, and suggests that the overexpression of LTC_4S described in tissues from patients with AERD[53] has a potentially causal role.

Prostaglandin E_2 (PGE_2) controls cys-LT generation by activating PKA and inducing phosphorylation of 5-LO.[79] Tissue inflammation is typically associated with increased PGE_2 production, reflecting the co-expression of 2 inducible enzymes; COX-2 (a largely aspirin-resistant enzyme) and microsomal PGE_2 synthase-1 (mPGES-1), which isomerizes COX-2-derived PGH_2 to PGE_2.[80] Nasal polyps from subjects with AERD contain less PGE_2 than nasal polyps from aspirin tolerant controls,[81] possibly relating to epigenetic modifications of COX-2[82] and/or mPGES-1 expression.[83] Mice lacking mPGES-1 (*Ptges–/–*) cannot upregulate PGE_2 production with inflammation, and display a remarkably AERD-like phenotype when subjected to a model of *Df*-induced pulmonary disease. Compared with WT controls, *Ptges–/–* mice show increased eosinophilic inflammation and levels of cys-LTs in the BAL fluid. Challenge with inhaled lysine aspirin causes marked increases in airway resistance, robust release of cys-LTs, and pulmonary mast cell activation in the *Ptges–/–* strain, but not in WT controls.[84] Aspirin challenge profoundly depletes lung PGE_2 in the *Ptges–/–* mice, but not in the WT controls, suggesting that the mPGES-1 is needed to maintain PGE_2 levels when COX-1 is inhibited. *Ptges–/–* mice also show increased numbers of platelet-adherent granulocytes in both the peripheral blood and lungs compared with WT controls. Importantly, cys-LT production, mast cell activation, and the changes in airway resistance were blocked by depletion of platelets or blockade of the TP receptor for thromboxane A_2. This model may be useful in defining the potential pathogenetic role of GPR99, $CysLT_2R$, and $P2Y_{12}$ receptors in AERD, as well as unraveling the complex interplay between cys-LTs, platelets, and mast cells that lead to the physiologic response to aspirin challenges.

CONCLUSIONS

While the drugs capable of inhibiting cys-LT formation and blocking $CysLT_1R$ are useful, it is clear that the cys-LT system is far more complex than initially appreciated. The involvement of the cys-LTs in the induction of Th2 immunity and the effector phase of the immune response suggests additional potential applications for currently available pharmacologic agents. However, the recognition that cys-LTs act through at least three receptors and the resistance of 2 of these ($CysLT_2R$ and GPR99) to the blockade by currently available drugs presents both challenges and opportunities for further therapeutic development. The availability of a broad array of valid animal models should facilitate progress in this area, while continuing to reveal unanticipated biological functions for the cys-LTs and their receptors.

ACKNOWLEDGMENTS

This work was supported by NIH grants AI078908, AI095219, AT002782, AI082369, HL111113, HL117945, and HL36110, and by the Vinik Family.

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