

T Helper Cell Type 2 Cytokines Coordinately Regulate Immunoglobulin E–dependent Cysteinyl Leukotriene Production by Human Cord Blood–derived Mast Cells: Profound Induction of Leukotriene C₄ Synthase Expression by Interleukin 4

By Fred H. Hsieh,^{*§} Bing K. Lam,^{*§} John F. Penrose,^{*§}
K. Frank Austen,^{*§||} and Joshua A. Boyce^{*‡§||}

From the ^{*}Department of Medicine and the [‡]Department of Pediatrics, Harvard Medical School, Boston, Massachusetts 02115; the [§]Division of Rheumatology, Immunology and Allergy, Brigham and Women's Hospital, Boston, Massachusetts 02115; and the ^{||}Partners' Asthma Center, Boston, Massachusetts 02115

Abstract

Human mast cells (hMCs) derived in vitro from cord blood mononuclear cells exhibit stem cell factor (SCF)–dependent comitogenic responses to T helper cell type 2 (Th2) cytokines. As cysteinyl leukotriene (cys-LT) biosynthesis is a characteristic of immunoglobulin (Ig)E-activated mucosal hMCs, we speculated that Th2 cytokines might regulate eicosanoid generation by hMCs. After passive sensitization for 5 d with IgE in the presence of SCF, anti-IgE–stimulated hMCs elaborated minimal cys-LT (0.1 ± 0.1 ng/10⁶ hMCs) and abundant prostaglandin (PG)D₂ (16.2 ± 10.3 ng/10⁶ hMCs). Priming of hMCs by interleukin (IL)–4 with SCF during passive sensitization enhanced their anti-IgE–dependent histamine exocytosis and increased their generation of both cys-LT (by 27-fold) and PGD₂ (by 2.5-fold). Although priming with IL–3 or IL–5 alone for 5 d with SCF minimally enhanced anti-IgE–mediated cys-LT generation, these cytokines induced further six- and fourfold increases, respectively, in IgE-dependent cys-LT generation when provided with IL–4 and SCF; this occurred without changes in PGD₂ generation or histamine exocytosis relative to hMCs primed with IL–4 alone. None of these cytokines, either alone or in combination, substantially altered the levels of cytosolic phospholipase A₂ (cPLA₂), 5-lipoxygenase (5-LO), or 5-LO activating protein (FLAP) protein expression by hMCs. In contrast, IL–4 priming dramatically induced the steady-state expression of leukotriene C₄ synthase (LTC₄S) mRNA within 6 h, and increased the expression of LTC₄S protein and functional activity in a dose- and time-dependent manner, with plateaus at 10 ng/ml and 5 d, respectively. Priming by either IL–3 or IL–5, with or without IL–4, supported the localization of 5-LO to the nucleus of hMCs. Thus, different Th2-derived cytokines target distinct steps in the 5-LO/LTC₄S biosynthetic pathway (induction of LTC₄S expression and nuclear import of 5-LO, respectively), each of which is necessary for a full integrated functional response to IgE-dependent activation, thus modulating the effector phenotype of mature hMCs.

Key words: eicosanoids • asthma • allergy • prostaglandin D₂ • FcεRI

Introduction

Mast cells (MCs)¹ are stem cell factor (SCF)–dependent hematopoietic cells that home to tissues as committed progenitors and then mature and differentiate into heterogeneous

phenotypes (1–3). When stimulated by their high-affinity Fc receptor for IgE (FcεRI), MCs generate a range of bioactive products implicated in allergic and asthmatic inflammation. Among these products are the eicosanoid metabo-

Address correspondence to J.A. Boyce, Smith 616, Brigham and Women's Hospital, 1 Jimmy Fund Way, Boston, MA 02115. Phone: 617-525-1233; Fax: 617-525-1242; E-mail: jboyce@rics.bwh.harvard.edu

¹Abbreviations used in this paper: BMDC, bone marrow–derived MC; cPLA₂, cytosolic phospholipase A₂; cys-LT, cysteinyl leukotriene; FcεRI,

high-affinity Fc receptor for IgE; FLAP, 5-LO activating protein; hMC, human MC; 5-LO, 5-lipoxygenase; LT, leukotriene; LTC₄S, LTC₄ synthase; MC, mast cell; PGD₂S, PGD₂ synthase; PGHS, prostaglandin endoperoxide H synthase; RP, reverse phase; SCF, stem cell factor.

lites of cell membrane-derived arachidonic acid: PGD₂ (4), a product of the prostaglandin endoperoxide H synthase (PGHS)/PGD₂ synthase (PGD₂S) pathway, and leukotriene (LT)C₄, a product of the 5-lipoxygenase (5-LO)/LTC₄ synthase (LTC₄S) pathway (5). Cell activation by FcεRI initiates both pathway sequences with liberation of membrane stores of arachidonic acid by a calcium-dependent cytosolic phospholipase A₂ (cPLA₂; reference 6). Constitutive PGHS-1 and inducible PGHS-2, integral proteins of the perinuclear membrane and endoplasmic reticulum, provide substrate, PGH₂, to cytosolic, glutathione-dependent PGD₂S (7–9). Human MCs (hMCs) release PGD₂ during the early bronchoconstrictor response to inhaled allergen challenge (10). PGD₂ may contribute to bronchoconstriction in aspirin-sensitive asthma (11) and to the development of allergic airway inflammation through its interaction with its receptor on bronchial epithelial cells (12).

In response to cell activation, 5-LO reversibly translocates from either the nucleoplasm or cytoplasm, depending on the cell type, to the perinuclear region (13), and acts in concert with 5-LO activating protein (FLAP [14]), an integral perinuclear protein, to convert arachidonic acid sequentially to the unstable intermediates 5-hydroperoxy-eicosatetraenoic acid (5-HPETE) and then to LTA₄ (15). LTA₄ either is converted by LTA₄ hydrolase (16) to LTB₄ (as occurs in neutrophils and monocytes) or is conjugated to reduced glutathione by LTC₄S (17–19), an integral perinuclear membrane protein with homology to FLAP that is expressed by eosinophils, basophils, MCs, and monocytes. LTC₄ is released by a distinct cellular export mechanism (20) and converted sequentially to the receptor-active cysteinyl LTs (cys-LTs), LTD₄ and LTE₄, by extracellular γ-glutamyl transferase and dipeptidase, respectively (21, 22). LTC₄, LTD₄, and LTE₄ then act at specific receptors, including the CysLT1 receptor (23) and CysLT2 receptor (24), to mediate a variety of cellular effects germane to asthma, including bronchoconstriction, alterations in venular permeability, leukocyte extravasation, and mucus hypersecretion (25–28). The role for the cys-LT in asthma is now substantiated by the clinical efficacy of pharmacologic agents that interfere with the actions of 5-LO or that block the CysLT1 receptor (29, 30).

hMCs differ in their profiles of eicosanoid biosynthesis in response to FcεRI-dependent activation after isolation from various dispersed tissue sources. Both total cys-LT generation (from 3.5 ng/10⁶ hMCs from skin to 45 ng/10⁶ hMCs from uterus) and the cys-LT/PGD₂ ratio (1:12 for skin hMCs; 1:3, 1:2, and 1:1 for lung, uterine, and intestinal hMCs, respectively) are marked by tissue-related differences that are both quantitative and relative (31–34). Because MCs in all tissues derive from a single lineage of circulating committed progenitors (2, 35, 36) under the influence of constitutively expressed SCF, we postulated that their heterogeneous profiles of eicosanoid generation would be determined by the absence or presence of additional local factors, particularly the cytokines derived from the Th2 lymphocytes that associate with mucosal surfaces in allergic diseases.

We recently reported the derivation in vitro of hMCs from umbilical cord blood mononuclear cells cultured in the presence of recombinant human SCF, IL-6, and IL-10 (37). These cells were characterized by uniformly high levels of *c-kit* expression, expression of CD13 and low-level FcεRIα, and uniform toluidine blue metachromasia and immunoreactivity for both tryptase and chymase. The receptors for IL-3 and IL-5 were detected on these hMCs by flow cytometry, and the corresponding recombinant ligands induced a comitogenic response when provided with SCF. We now demonstrate that IL-4, in addition to its recognized inductive effect on FcεRI expression (38), strongly and selectively upregulates the expression of LTC₄S mRNA, protein, and biosynthetic function. However, the inclusion of either IL-3 or IL-5 with IL-4 during priming selectively further increases IgE-dependent cys-LT production by hMCs, without altering PGD₂ production, by favoring nuclear import of 5-LO. Thus, the distinct effects of Th2 cytokines control the integrated function of the 5-LO/LTC₄S pathway in SCF-dependent hMCs.

Materials and Methods

Cytokines. Recombinant human SCF was a generous gift from Amgen. The cytokines IL-3, IL-4, and IL-5 (PeproTech), IL-6 (R&D Systems), and IL-10 (Endogen) were purchased as noted.

Cell Culture. Cord blood was obtained from human placentas after routine Caesarian section in accordance with established institutional guidelines. hMCs were derived by the culture of the mononuclear cell fraction as described previously (37). In brief, heparin-treated cord blood was sedimented with 4.5% dextran solution to remove erythrocytes. The buffy coats were layered onto 1.77 g/liter Ficoll-Hypaque (Amersham Pharmacia Biotech), and mononuclear cell interfaces were obtained after centrifugation. Residual erythrocytes were removed by hypotonic lysis, and the remaining mononuclear cells were suspended in RPMI 1640 (GIBCO BRL) containing 10% fetal bovine serum, 2 mM L-glutamine, 0.1 mM nonessential amino acids, 100 U/ml penicillin, 100 mg/ml streptomycin, 2 μg/ml gentamycin (all from Sigma-Aldrich), and 0.2 μM 2-mercaptoethanol (GIBCO BRL). Cells were seeded at a concentration of 10⁶ cells/ml and were cultured in the presence of 100 ng/ml SCF, 50 ng/ml IL-6, and 10 ng/ml IL-10. The nonadherent cells were transferred every week for up to 9 wk into culture medium containing fresh cytokines. Cytospin preparations were examined weekly from samples of 2 × 10⁴ cells using a cytocentrifuge (Shandon) and were stained with toluidine blue to assess metachromasia. Once cells reached maturity, defined by >95% toluidine blue positivity and positive immunostaining for both tryptase and chymase (37), no other immunocytochemical or functional differences were noted between 6- and 9-wk cells. Therefore, cells were used for this study when they reached >95% toluidine blue positivity rather than a specific number of weeks in culture. No quantitative or qualitative changes in cell responsiveness to cytokine treatments were observed that were age dependent.

Analysis of Cys-LT and PGD₂ Production and Histamine Release by hMCs after Passive IgE Sensitization and Anti-IgE Activation. hMCs were washed twice in medium alone and were resuspended in medium containing SCF (100 ng/ml) and semipurified human myeloma IgE (10 μg/ml; Chemicon). Cells were incu-

bated with combinations of additional cytokines, including IL-3 (5 ng/ml), IL-4 (10 ng/ml), and IL-5 (5 ng/ml). The 10 ng/ml concentration of IL-4 and the 5-d period of priming were each chosen so as to optimize the expression and function of Fc ϵ RI (38). The concentration of IL-3 was selected based on preliminary dose-response experiments for cys-LT generation with 10 ng/ml IL-4 and SCF. The concentration-response for 1, 5, and 10 ng/ml IL-3 on IL-4-primed hMCs was 3.4, 16.0, and 25.5 ng cys-LT/10⁶ hMCs, respectively. The dose of 5 ng/ml IL-3 was chosen as it was also the optimal concentration for comitogenesis (37). The dose of IL-5 was chosen for similar reasons. The hMCs were stimulated with a rabbit anti-human IgE Ab (ICN Biomedicals) at a concentration of 1 μ g/ml for 30 min at 37°C. Cell supernatants were harvested and stored at -70°C before assay. Cell pellet fractions were resuspended in medium and lysed by three cycles of rapid freezing and thawing. Histamine in the supernatant and cellular pellet fractions was measured by histamine ELISA (ICN Biomedicals). Percentage of histamine release was quantitated by the equation: histamine in supernatant/(histamine in supernatant + histamine in pellet) \times 100. Cys-LT generation in the supernatant was measured with an ELISA for LTC₄/D₄/E₄ (Amersham Pharmacia Biotech). For this ELISA, the cross-reactivity with LTC₄ is 100%, LTD₄ is 100%, LTE₄ is 70%, and LTB₄ is 0.3%. PGD₂ generation in the supernatant was measured with an ELISA for PGD₂ (Cayman Chemical). For the PGD₂ ELISA, the cross-reactivity with TXB₂, PGF_{2 α} , or PGE₂ is <0.01%. The ratios of cys-LT to PG-D₂ were calculated as the mean \pm SD of the respective ratios determined for each condition in each individual experiment.

For measurement of cys-LT generation by reverse phase (RP)-HPLC, hMCs were primed and activated as above. Cell supernatants were collected and three volumes of cold methanol containing 400 ng/ml of PGB₂ were added. After centrifugation in a microcentrifuge (Eppendorf) for 5 min at maximum speed at room temperature, the clarified methanolic extracts were removed and applied to a 5- μ m 4.6 \times 250 mm C18 Ultrasphere RP-HPLC column (Beckman Coulter) equilibrated with 100% methanol/ acetonitrile/water/acetic acid (10:15:100:0.2, vol/vol, pH 6.0; solvent A). RP-HPLC was performed with a model 126 dual pump system and a model 167 scanning UV detector (Beckman Instruments) with Beckman System Gold software. After injection of the sample, the column was eluted at a flow rate of 1 ml/min with a programmed concave gradient (System Gold curve 6) to 55% of the equilibrated solvent A and 45% methanol (solvent B) over 2.5 min. After 5 min, solvent B was increased linearly to 75% over the next 15 min and was maintained at this level for an additional 15 min. UV absorbance at 235 and 280 nm was recorded. The retention times for PGB₂, LTB₄, LTC₄, LTD₄, LTE₄, and 5-HETE were 20.7, 24.0, 21.6, 23.6, 26.0, and 30.2 min, respectively. The resolved products were quantitated by calculating the ratio of the peak areas to the area of the internal standard PGB₂ (18). When synthetic LTC₄ or mixtures of synthetic LTD₄ and LTE₄ (Cayman Chemical) were analyzed using both RP-HPLC and ELISA, the total product measured by ELISA was consistently greater than that measured by RP-HPLC by a maximum of 20%.

SDS-PAGE Immunoblot Analysis. Whole cell extracts were prepared by washing cells in cold PBS and then boiling them in Tris-glycine/bromophenol blue lysis buffer (Novex) containing 0.5% 2-ME at a concentration of 10⁷ cells/ml of lysis buffer for 10 min. After SDS-PAGE with 14% Tris-glycine gels (Novex), the proteins from 10⁵ cells/lane were electrophoretically transferred to 0.45- μ m nitrocellulose membranes (Bio-Rad Laborato-

ries). Nonspecific binding was blocked with 3% wt/vol nonfat milk (Bio-Rad Laboratories) in Tris-buffered saline (TBS) containing 0.1% wt/vol Tween 20 and 0.5% normal goat serum (Caltag). Detection of LTC₄S with primary Abs used a 1:500 dilution of affinity-purified rabbit polyclonal antipeptide Ab (0.192 mg/ml) directed against the carboxyl-terminal 15 amino acids of human LTC₄S (protein sequence RAALLGRLRTLWPA). This Ab does not cross-react with human FLAP, human m-glutathione-S-transferase II, or mouse LTC₄S on immunoblot, and recognizes only human LTC₄S in multiple tissue and cellular lysates. Additional primary Abs used in this study included rabbit polyclonal anti-5-LO Ab (J. Evans, Merck-Frosst Centre, Quebec, Canada [15]) at 1:5,000 dilution, rabbit polyclonal anti-FLAP Ab (15) at 1:5,000 dilution, and rabbit polyclonal anti-cPLA₂ Ab (Santa Cruz Biotechnology, Inc.) at 1:1,000 dilution. After the membranes were washed, the proteins were detected with a secondary goat anti-rabbit IgG labeled with horseradish peroxidase (Bio-Rad Laboratories) followed by enhanced chemiluminescence (ECL; Amersham Pharmacia Biotech). SDS-PAGE immunoblots were quantitated using a ChemImager 4400 densitometer with AlphaEase v5.0 software (Alpha Innotech Corporation).

RNA Blot Analysis. Total RNA was extracted from 10⁷ cells with Tri-reagent (Molecular Research Center [39]). After extraction with chloroform followed by overnight precipitation in isopropanol, total RNA was washed with 70% ethanol and purity was assessed by spectrophotometry (DU 640; Beckman Coulter). Then, 14 μ g of total RNA was loaded into a 1.2% agarose gel with 1 \times MOPS (3-[N-morpholino] propan-sulfonic acid) buffer containing 20% formaldehyde. After electrophoresis, RNA was transferred to nylon membranes (Micron Separations) by capillary action overnight. RNA was fixed to the membrane by baking at 80°C for 1 h. The blot was prehybridized in 5 \times standard sodium phosphate with EDTA (SSPE; GIBCO BRL) containing 2 \times Denhardt's solution, 0.25% SDS, 50% formamide, and 100 μ g/ml denatured salmon sperm DNA (GIBCO BRL) overnight at 43°C. The blot was then probed with human LTC₄S cDNA (18) or human 18S ribosomal RNA (CLONTECH Laboratories, Inc.) that had been labeled with [³²P]dCTP incorporated by random priming with RediPrime II (Amersham Pharmacia Biotech). Blots were washed at high stringency with 0.2 \times SSPE at 55°C, and hybridization signals were detected by autoradiography with Kodak XAR film (Eastman Kodak Co.).

Analysis of LTC₄S Activity in Lysed Cells. LTC₄S activity was determined as described (18, 39). 2 \times 10⁵ hMCs were washed into 250 μ l of 50 mmol/liter of Hepes, pH 7.6, with 10 mmol/liter MgCl₂. The cells were sonicated on ice with a Branson sonicator three times for 5 s each. Reduced glutathione and LTA₄ methyl ester were added to the cell lysates at room temperature at final concentrations of 10 mmol/liter and 20 μ mol/liter, respectively. After 10 min, the reaction was terminated by adding 2 volumes of cold methanol containing 400 ng/ml of PGB₂. After centrifugation in a microcentrifuge (Eppendorf) for 5 min at maximum speed, the supernatants were removed and applied to a 5- μ m 4.6 \times 250 mm C18 Ultrasphere RP-HPLC column (Beckman Coulter) equilibrated with 100% methanol/acetonitrile/water/acetic acid (10:15:100:0.2, vol/vol, pH 6.0; solvent A). After injection of the sample, the column was eluted at 1 ml/min with a programmed concave gradient (System Gold curve 6) to 30% of the equilibrated solvent A and 70% methanol (solvent B) over 0.2 min. After 2.8 min, solvent B was increased linearly to 90% over 2 min and was maintained at this level for an additional 10 min. UV absorbance at 280 nm and the UV spectra

were recorded. The retention times for PGB₂ and LTC₄ methyl ester were 8.5 and 10.1 min, respectively. LTC₄ methyl ester was quantitated by calculating the ratio of the peak area to the area of the internal standard PGB₂.

Immunofluorescence and Immunocytochemistry. hMCs were fixed in suspension with 2% paraformaldehyde in PBS for 10 min at 4°C, washed once in HBSS without calcium or magnesium containing 0.1% BSA (HBA), permeabilized with 100% methanol for 20 min at -20°C, and spun for 5 min at 500 rpm in a cytocentrifuge onto glass coverslips. The slides were then blocked in HBA containing 5% normal horse serum (Jackson ImmunoResearch Laboratories) for 1 h. Primary Abs rabbit polyclonal anti-5-LO Ab (J. Evans, Merck-Frosst Centre [15]) or normal rabbit IgG (Chemicon) were added at a 1:800 dilution in HBA, and the cells were incubated for 1 h at room temperature. The cells were then washed in HBA and treated for 1 h at room temperature with the nuclear dye bis-benzimide (Hoechst no. 33258; Sigma-Aldrich) at a 1:1,000 dilution and/or goat anti-rabbit IgG conjugated to FITC (Jackson ImmunoResearch Laboratories) at a 1:100 dilution. After washing in HBA, cells were mounted in a 33% glycerol solution in PBS containing 15% w/v vinol 205 (Air Products and Chemicals) and 0.1% sodium azide. Cells were visualized with 40× or 100× oil objective lenses with a FXA microscope (Nikon). At least 100 cells per cover slip were counted in each experiment. The presence or absence of nuclear staining was determined by superimposition of the FITC-stained images with the Hoechst-stained images of the same cells. Each cover slip was scored for nuclear staining of 5-LO by two independent investigators blinded to the experimental conditions. The results reported are the average of the percentage of positive cells reported by the two investigators for each experiment.

For immunocytochemistry, slides with 2×10^4 hMCs were prepared by cytocentrifugation, air dried, and fixed in Carnoy's fluid (60% ethanol, 30% chloroform, and 10% glacial acetic acid) for 10 min at room temperature. After being washed with PBS three to four times, the slides were blocked with 2% chicken egg albumin (Sigma-Aldrich) for 30 min at room temperature, and were incubated with an appropriate dilution of antitryptase (Chemicon) or with an equivalent dilution of the corresponding isotype-matched negative control (BD PharMingen). After application of the appropriate secondary Ab, alkaline phosphatase was used as a chromogenic reporter (37).

Statistical Analysis. Unless otherwise indicated, the results are reported as the mean \pm SEM from at least three independent experiments with the cells from different donors. As consistent trends for cytokine effects on cys-LT generation were observed despite wide variability among subjects in absolute quantities produced, the data for eicosanoid generation were calculated both as absolute quantities and as the mean ratio of cys-LT/PGD₂ for each experiment. Statistical differences in immunostaining and eicosanoid generation were determined with the independent group Student's *t* test.

Results

Effect of Th2-type Cytokines on Cys-LT and PGD₂ Generation by Anti-IgE-activated hMCs. hMCs developed from human umbilical cord blood mononuclear cells cultured in the presence of SCF, IL-6, and IL-10 (37) were washed and maintained with SCF (100 ng/ml) alone or with SCF plus IL-4 (10 ng/ml) for 5 d of passive sensitization with human IgE. When activated by the addition of anti-IgE,

hMCs primed by IL-4 released fivefold more of their secretory granule-associated histamine than hMCs stimulated after maintenance with SCF alone ($P = 0.0006$, $n = 4$; Fig. 1), compatible with previous reports (38, 40). hMCs treated with SCF alone during passive sensitization generated only 0.1 ± 0.1 ng cys-LT/ 10^6 cells, whereas those primed with IL-4 in the presence of SCF responded to IgE-dependent activation with a 27-fold increase in cys-LT production (2.7 ± 1.0 ng cys-LT/ 10^6 cells, $P = 0.03$, $n = 4$; Fig. 1). PGD₂ generation by hMCs in SCF alone increased from a substantial amount (16.2 ± 10.3 ng/ 10^6 hMCs) to 39.1 ± 18.5 ng/ 10^6 hMCs ($P = 0.17$, $n = 4$; Fig. 1) when the cells were primed with IL-4. IL-4 priming produced an increment in both cys-LT and PGD₂ production in every experiment.

The modest cys-LT generation even after IL-4-induced priming for IgE-dependent activation prompted a search for additional priming factors, with attention to the Th2 cytokines that had previously shown maximal comitogenic activities for hMCs, IL-3, and IL-5. Priming with IL-3 alone produced a small increment in IgE-dependent cys-LT

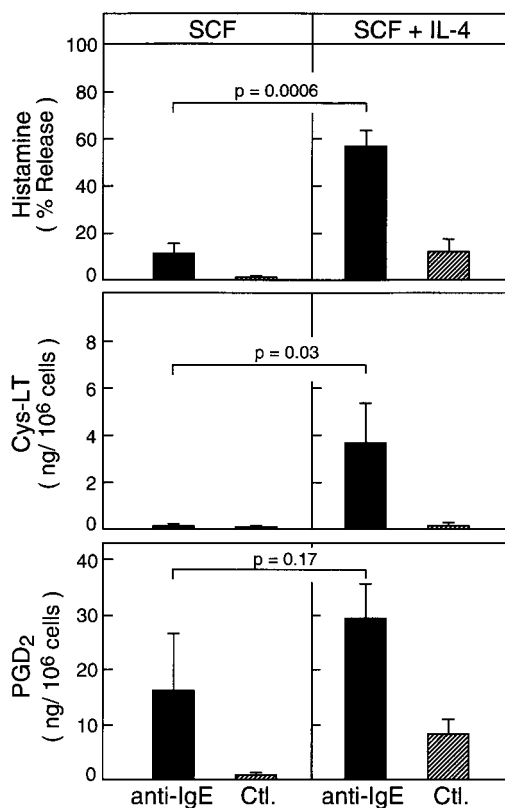


Figure 1. Effect of IL-4 priming of hMCs on IgE-mediated histamine release and eicosanoid generation as measured by ELISA. hMCs were maintained in SCF and IgE for 5 d with and without 10 ng/ml of IL-4. Results depict percent histamine release, cys-LT generation, and PGD₂ production after 5 d of priming and passive sensitization followed by activation with anti-IgE (black bars) or treatment with buffer alone (hatched bars). Results are the mean \pm SEM of four experiments and the IL-4 effect was significant for histamine ($P = 0.0006$) and cys-LT ($P = 0.03$). Ctl., control.

generation above cells maintained in SCF alone that was evident by 24 h and maximal by 3 d (2.7 ± 2.0 ng vs. 0.9 ± 1.8 ng, $n = 3$). Priming with IL-5 was comparable ($n = 1$). When added with SCF and IL-4 for 5 d of priming, neither IL-3 (5 ng/ml) nor IL-5 (5 ng/ml) increased the exocytosis of histamine by passively sensitized hMCs challenged with anti-IgE ($55 \pm 9\%$ and $53 \pm 9\%$ release with the added priming of IL-3 and IL-5, respectively, vs. $73 \pm 8\%$ release with IL-4 priming alone, $n = 4$; Fig. 2). In contrast, in each of these experiments, the inclusion of IL-3 during priming with IL-4 increased IgE-dependent cys-LT generation (from 5.7 ± 3.1 to 33.0 ± 13.1 ng/ 10^6 hMCs, $P = 0.05$, $n = 5$). The effect of IL-5 priming was similar and present in every experiment (22.7 ± 16 ng/ 10^6 hMCs, $P = 0.17$, $n = 3$; Fig. 2). Priming by IL-3 plus IL-4 also modestly increased PGD₂ generation relative to priming with IL-4 alone (from 27.2 ± 5.4 to 40.3 ± 12.3 ng/ 10^6 hMCs, $n = 4$), whereas IL-5 did not add to the effect of IL-4 priming alone for PGD₂ generation (28.3 ± 2.0 ng/ 10^6 hMCs, $n = 3$; Fig. 2). Because the effects of IL-3 and IL-5 were each relatively selective for cys-LT generation, their addition significantly altered the ratio of cys-LT to PGD₂

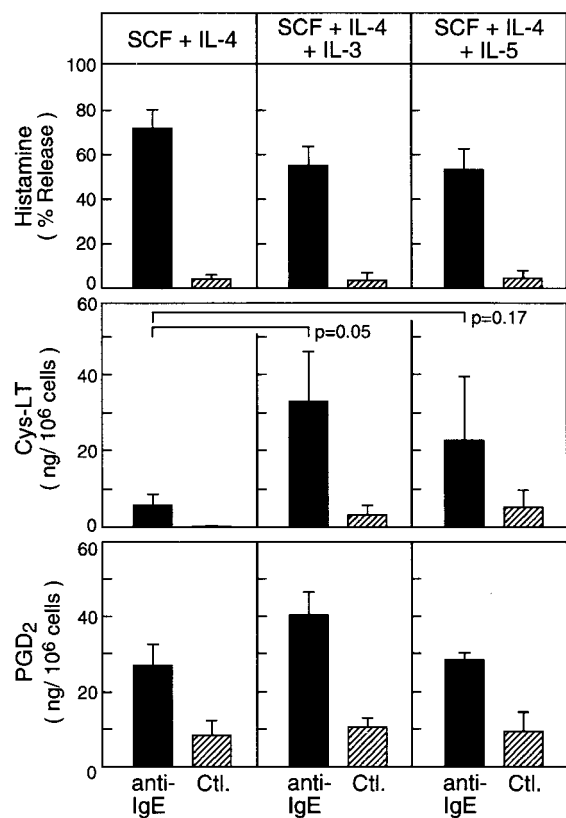


Figure 2. Effect of IL-3 or IL-5 treatment during IL-4 priming of hMCs for IgE-mediated release of histamine and generation of cys-LTs and PGD₂, as measured by ELISA. hMCs were activated with anti-IgE (black bars) or buffer (hatched bars) after 5 d of passive sensitization and priming with IL-4 in the presence of SCF with or without the addition of IL-3 or IL-5. Results are mean \pm SEM for five (for SCF plus IL-4 and SCF plus IL-4 plus IL-3) or three (SCF plus IL-4 plus IL-5) experiments. Ctl., control.

generated (from 1:14.6 for hMCs primed with IL-4 to 1:2.9 for hMCs primed with IL-3 plus IL-4 [$P = 0.05$] and 1:3.7 for hMCs primed with IL-5 plus IL-4 [$P = 0.04$]).

The effects of each cytokine on integrated cellular 5-LO function can be quantitatively assessed only by RP-HPLC analysis, permitting the simultaneous measurement of cys-LT, LTB₄, and the proximal metabolites 5-HETE and 6-trans-LTB₄ (derived from nonenzymatic breakdown of 5-HPETE and LTA₄, respectively). With this analysis, hMCs maintained with SCF alone generated 0.1 ± 0.2 pmoles cys-LT/ 10^6 hMCs with IgE-dependent activation, whereas hMCs primed with IL-3 in the absence of IL-4 produced 2.7 ± 1.3 pmoles cys-LT/ 10^6 hMCs ($n = 3$ for both conditions). Comparable quantities were produced by IL-5-primed hMCs. hMCs primed by IL-4 with SCF generated 5.0 ± 2.4 pmoles cys-LT/ 10^6 hMC ($n = 5$) after activation, which was increased threefold by the inclusion of IL-3 (14.8 ± 4.2 pmoles/ 10^6 hMCs, $P = 0.05$, $n = 4$), and to a lesser extent by the inclusion of IL-5 (8.6 ± 2.9 ng/ 10^6 hMCs, $P = 0.19$, $n = 3$). No 5-HETE or 6-trans LTB₄ was detected under any experimental conditions. Peaks corresponding to LTC₄, LTD₄, and LTE₄ were detected, with most of the product being converted to LTE₄.

Effect of Th2 Cytokines on LTC₄S Expression and Function. Compared with maintenance in SCF alone, priming by IL-4 (10 ng/ml) for 5 d resulted in a marked increase in LTC₄S protein, with a slight increase in cPLA₂ and no apparent change in either FLAP or 5-LO (Fig. 3 a). As quantitated by densitometry, the mean increase in LTC₄S protein signal after IL-4 treatment was fivefold (Fig. 3 b; $n = 11$, $P = 0.0005$). IL-13 (10 ng/ml) did not affect the expression of LTC₄S or any of the other pathway proteins, as shown for LTC₄S (Fig. 4 a). With the concentration of SCF held constant at 100 ng/ml, treatment of hMCs for 5 d with increasing concentrations of IL-4 induced a dose-dependent increase in immunodetectable LTC₄S protein in every

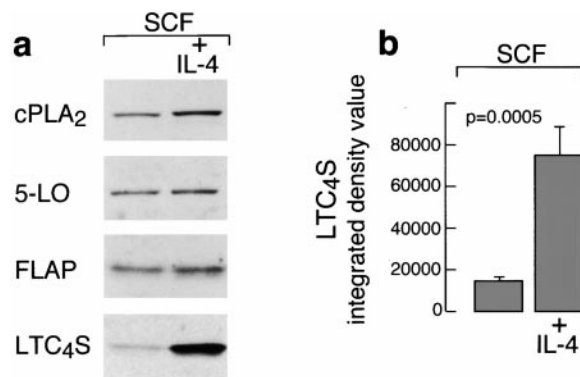


Figure 3. Effect of IL-4 priming on 5-LO/LTC₄S pathway protein expression by hMCs. (a) SDS-PAGE immunoblot was performed with lysates from hMCs (10^5 /lane), treated for 5 d with SCF with or without IL-4, with polyclonal Abs specific for cPLA₂, 5-LO, FLAP, and LTC₄S, as specified in Materials and Methods. The displayed blot is a single experiment representative of three experiments. (b) Quantitative densitometry revealed a fivefold increase in LTC₄S signal after IL-4 treatment for 5 d ($n = 11$, $P = 0.0005$).

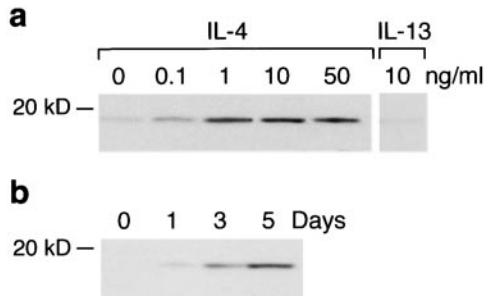


Figure 4. Dose dependence and kinetics for the IL-4-mediated upregulation of LTC₄S protein expression. (a) Dose-dependent effects at 5 d of IL-4, from 0.1 to 50 ng/ml, on LTC₄S protein with a constant concentration of SCF (100 ng/ml), as demonstrated by SDS-PAGE immunoblot. Single lanes containing lysates from 10⁵ hMCs treated for 5 d with SCF alone, and with SCF plus IL-13 (10 ng/ml), are included. (b) Kinetic effects of IL-4 (10 ng/ml) on LTC₄S protein in hMCs incubated for 0 to 5 d with SCF (100 ng/ml) to maintain viability. The displayed blots are representative of three experiments each.

experiment ($n = 3$), apparent at the lowest concentration tested (0.1 ng/ml), and maximal at 10 ng/ml (Fig. 4 a). The effect of 10 ng/ml IL-4 on LTC₄S protein was apparent by 1 d and maximal at 5 d (Fig. 4 b). LTC₄S activity, as measured by the conversion of LTA₄ methyl ester to LTC₄ methyl ester, remained unchanged in lysates of hMCs treated with SCF alone for 1 and 5 d as compared with hMCs harvested from the original developmental triad of SCF, IL-6, and IL-10. In contrast, lysates of IL-4-primed hMCs revealed a sevenfold increase in LTC₄S activity over this time frame (138.5 pmol to 980.5 pmol LTC₄/10⁶ hMCs, $n = 4$, $P = 0.02$; Fig. 5). Compared with maintenance in SCF alone, the addition of IL-4 (10 ng/ml) enhanced steady-

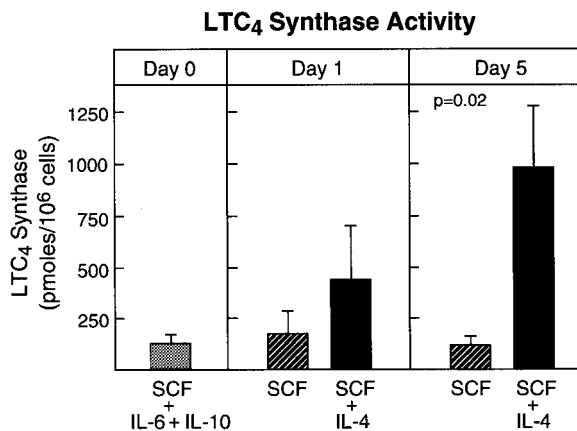


Figure 5. IL-4-mediated upregulation of LTC₄S biosynthetic activity. LTA₄ methyl ester and reduced glutathione were provided as substrates to the sonicated lysates from 2×10^5 hMCs for each condition. Sonicates were prepared from hMCs harvested from their original medium containing SCF, IL-6, and IL-10 at the start of the experiment (day 0), and again after these hMCs were treated with SCF alone (100 ng/ml) or with SCF and IL-4 (10 ng/ml) for the indicated times. Products were resolved by RP-HPLC and quantitated based on the internal standard PGB₂ as indicated in Materials and Methods. Results are mean \pm SEM for four experiments.

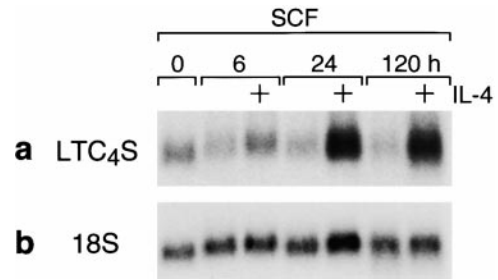


Figure 6. IL-4-mediated upregulation of steady-state LTC₄S mRNA. (a) RNA blot analysis depicting hybridization signals for LTC₄S mRNA in samples of total RNA (14 μ g/lane) extracted from hMCs that were harvested at the indicated times after being transferred to fresh SCF-containing medium with (+) or without IL-4. (b) Ribosomal 18S RNA signal in the corresponding lanes. Results are representative of two experiments performed.

state levels of LTC₄S mRNA expression by 6 h, with a plateau at 24 h that continued unchanged for 5 d ($n = 2$, as shown for a representative experiment; Fig. 6).

Effect of IL-3 and IL-5 on the Cellular Localization of 5-LO. Compared with hMCs primed with SCF alone, neither IL-3 nor IL-5 priming altered the immunodetectable quantities of 5-LO or FLAP, and they modestly increased the baseline expression of cPLA₂. IL-5, but not IL-3, also slightly increased immunodetectable LTC₄S protein (Fig. 7). When added in combination with IL-4 in the presence of SCF, neither IL-3 nor IL-5 produced further increases in LTC₄S protein or altered the quantities of 5-LO or FLAP proteins, and each induced slight increases in the expression of cPLA₂ above that induced by IL-4 alone ($n = 3$, data not shown).

hMCs maintained for 5 d in SCF alone displayed weak 5-LO immunoreactivity predominantly in a diffuse, cytoplasmic distribution (as shown for one experiment; Fig. 8 d). Under these conditions, $11 \pm 2\%$ of the hMCs exhibited some staining of the nucleus after 5 d, which was enhanced only slightly by the addition of IL-4 ($19 \pm 6\%$, $P =$

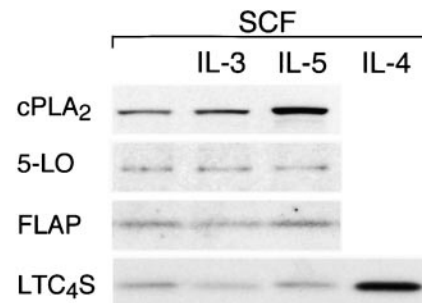


Figure 7. Effect of IL-3 or IL-5 priming on 5-LO/LTC₄S pathway protein expression by hMCs. SDS-PAGE immunoblot was performed with lysates from hMCs (10^5 /lane), treated for 5 d with SCF (100 ng/ml) with or without IL-3 or IL-5 (5 ng/ml each), using polyclonal Abs specific for cPLA₂, 5-LO, FLAP, and LTC₄S as specified in Materials and Methods. The LTC₄S signal from hMCs primed for 5 d with IL-4 is included for comparison. The displayed blot is a single experiment representative of three experiments.

0.12). When compared with maintenance in SCF alone or with SCF plus IL-4, treatment with either IL-3 or with IL-5 increased the proportion of hMCs exhibiting nuclear staining for 5-LO by as early as 3 d. The differences were significant by 5 d ($46 \pm 12\%$ with nuclear staining for

hMCs maintained with IL-3 and IL-4 plus SCF, $P = 0.05$; and $38 \pm 7\%$ for hMCs maintained with IL-5 and IL-4 plus SCF, $P = 0.03$). IL-3 and IL-5 each also increased the intensity of the nuclear stain ($n = 3$, as shown for a representative experiment; Fig. 8, h and j, respectively). The ef-

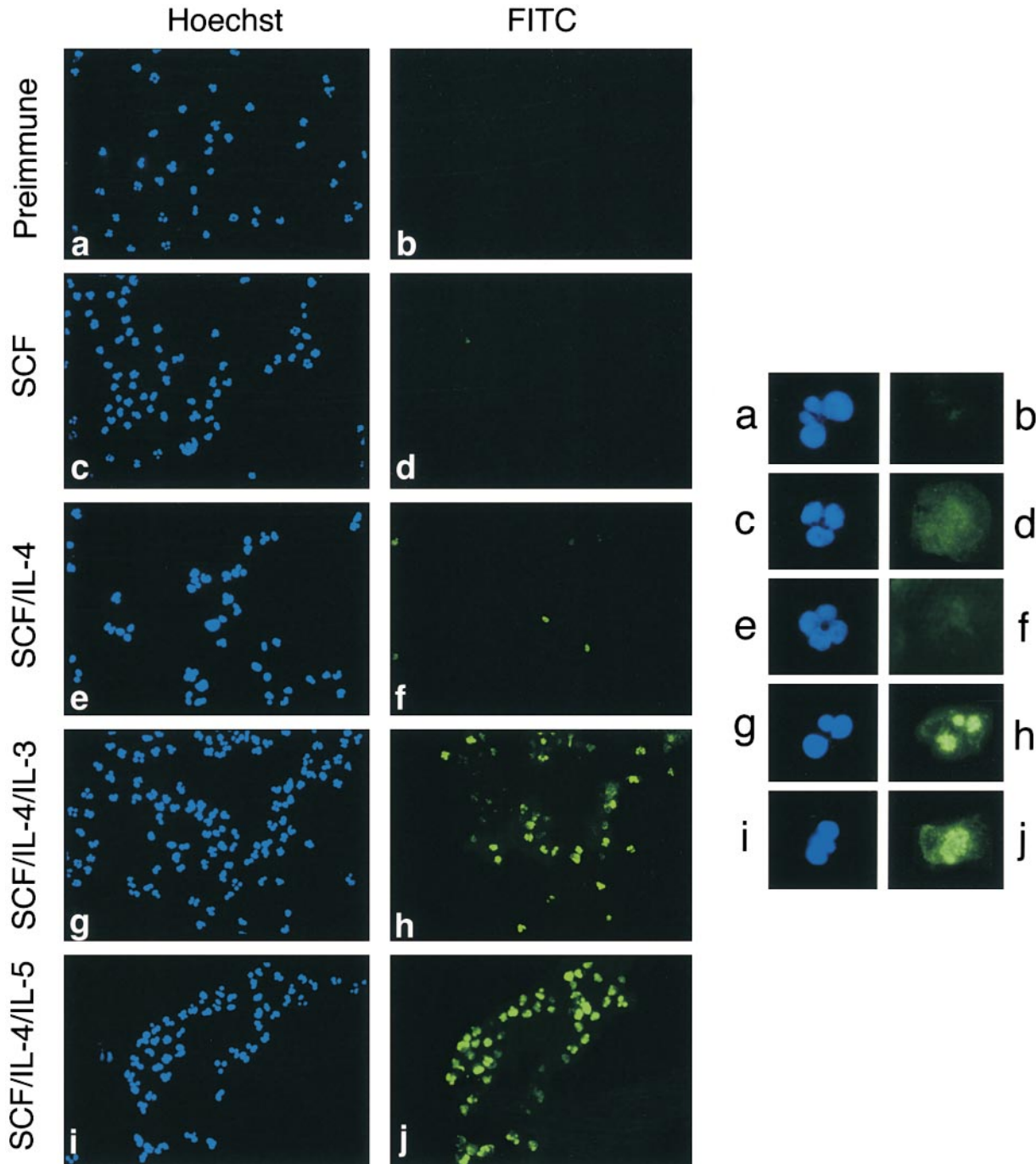


Figure 8. Effects of IL-3 and IL-5 on immunolocalization of 5-LO in hMCs. hMCs were maintained for 5 d in SCF alone (a–d), with 10 ng/ml of IL-4 (e and f), with IL-4 plus 5 ng/ml of IL-3 (g and h), or IL-4 plus 5 ng/ml of IL-5 (i and j). Images on the left are photographed through a 40 \times objective, whereas those on the right are photographed at 100 \times for nuclear detail. Identical fields of hMCs are photographed under blue fluorescence (a, c, e, g, and i) to show location of nuclei as identified by Hoechst staining, and under green fluorescence (FITC) to demonstrate localization of 5-LO immunoreactivity in the same cells (d, f, h, and j). FITC staining with a preimmune rabbit IgG (b) is included as a specificity control. The images are taken from a single experiment representative of three performed, for which the mean data are presented in the text.

fects of IL-3 and IL-5 on 5-LO localization were similar in experiments where IL-4 was omitted ($55 \pm 19\%$ and $34 \pm 14\%$ positive, respectively, mean $\pm 1/2$ range for two of the experiments presented above). Immunofluorescence with control rabbit IgG gave almost no background staining (Fig. 8 b).

Discussion

The effector molecules implicated in the pathogenesis of bronchial asthma include the lipid mediators provided by hMCs and eosinophils (10, 25, 41) and the cytokines provided by Th2 cells. hMCs derived from cord blood with the triad of SCF, IL-6, and IL-10 express the receptors for IL-3 and IL-5 (37), and both of these Th2 cytokines mediate comitogenic responses from hMCs in the presence of SCF. hMCs respond to a third Th2 cytokine, IL-4, with augmented Fc ϵ RI expression and IgE-dependent activation responses (38, 40). IL-3 and IL-5 promote the development in vitro of cord blood-derived eosinophils that express all proteins of the 5-LO/LTC₄S pathway (39) and that generate cys-LT after stimulation with calcium ionophore. Unlike eosinophils, which do not produce PGD₂, hMCs generate both PGD₂ and cys-LT, the latter of which exhibits wide variability among hMCs obtained from various dispersed tissues (31–34). Thus, both arms of the eicosanoid-generating pathways of hMCs were assessed for the regulatory effects of Th2 cytokines. We found that although cord blood-derived hMCs maintained in SCF alone generated abundant PGD₂ after IgE-dependent activation even without Th2 cytokine priming, their optimal cys-LT generation required the coordinate actions of IL-4 with either IL-3 or IL-5, which mediate separate and distinct steps in priming the 5-LO/LTC₄S pathway for an integrated functional response.

For all priming conditions, SCF was included to ensure maximal hMC viability. A marked (27-fold) increase in cys-LT generation (Fig. 1) was observed when hMCs were primed with IL-4 before activation. This was attributable to two events. First, IL-4 priming augmented IgE-dependent exocytosis of histamine by fourfold (Fig. 1), an effect attributable to the previously recognized upregulation of Fc ϵ RI by IL-4 (38, 40). Second, and unexpectedly, IL-4 induced a dramatic upregulation of LTC₄S transcript (Fig. 6), protein (Figs. 3 and 4), and function (Fig. 5). This marked induction by IL-4 was relatively selective for LTC₄S among the 5-LO/LTC₄S pathway proteins (Fig. 3). IL-13 at a concentration of 10 ng/ml did not upregulate LTC₄S protein (Fig. 4). In previous studies, IL-13 failed to augment Fc ϵ RI expression by cord blood hMCs (38), and was not comitogenic with SCF (37). The fact that hMCs respond markedly to IL-4 but not to IL-13 suggests that they may express the $\alpha\gamma$ IL-4 receptor heterodimer associated with T cells rather than the IL-4 receptor type II consisting of the IL-4R α and IL-13R α 1 subunits found mainly in B cells and nonhematopoietic cells (42). The parallel IL-4-mediated regulation of both Fc ϵ RI and LTC₄S, the biosynthetic enzyme responsible for cys-LT leukotriene gen-

eration, would fit the pivotal role of Th2 cells in bronchial asthma and supports a direct regulatory role for lymphocytes in the control of hMC function.

Although IL-4 priming of hMCs did induce their IgE-dependent cys-LT generation, the modest quantities of cys-LTs produced, relative to the abundant generation of PGD₂, led us to explore possible additional priming events. IL-3 and IL-5 were maximally comitogenic for hMCs from among a panel of Th2 cytokines tested in our earlier studies (37). When added without IL-4, IL-3 or IL-5 provided an increment in cys-LT production comparable to IL-4 alone by hMCs after IgE-dependent activation. In contrast, the inclusion of IL-3 or IL-5 with IL-4 resulted in a six- or fourfold increase, respectively, in IgE-dependent cys-LT production, without a dramatic change in either PGD₂ generation or percentage of histamine release (Fig. 2). These findings indicate a selective action of IL-3 and IL-5 on the function of the 5-LO/LTC₄S pathway. The priming effect of IL-3 and IL-5 involved the redistribution of 5-LO to the hMC nucleus (Fig. 8), which did not require the presence of IL-4, and was temporally concomitant with a functional effect evident by incremental cys-LT generation. Our studies thus reveal two Th2-dependent requirements for the integrated function of the 5-LO/LTC₄S pathway in cultured hMCs. IL-4 is necessary to upregulate Fc ϵ RI expression and to induce LTC₄S expression, whereas IL-3 or IL-5 positions 5-LO for its subsequent utilization of arachidonic acid in the presence of FLAP at the nuclear envelope after IgE-dependent activation. Neither event alone is sufficient for the full expression of cys-LT production, but each acts synergistically with the other to promote a marked phenotypic change in hMCs.

The human LTC₄S gene is localized to chromosome 5q35 (43), close to a locus identified by linkage analysis to have gene candidates for asthma and atopy (44, 45). Regulatory cis-acting elements and transcription factors for the proximal core promoter of the human LTC₄S gene in THP-1 cells include a non-cell-specific basal promoter and a cell-specific upstream enhancer region (46). The effect of IL-4 on LTC₄S expression may reflect increased LTC₄S transcription or could result from increased mRNA stability. A monocyte-like cell line, THP-1, responds to TGF- β with increased steady-state LTC₄S mRNA expression by a transcription-dependent mechanism, without an effect on LTC₄S transcript stability (47). IL-4 could also influence trafficking of nascent LTC₄S protein to the perinuclear membrane and endoplasmic reticulum. The latter may account for the lag between plateau mRNA expression (24 h) and protein expression (5 d) in this study. Maximal expression of LTC₄S steady-state mRNA also preceded the plateau for expression of immunodetectable LTC₄S protein by several days in culture-derived eosinophils (39). The findings in earlier studies that IL-3- and IL-5-driven eosinophil differentiation from cord blood progenitors in vitro was accompanied by marked induction of LTC₄ transcript and protein (39), and the findings in this study that maximal expression of LTC₄S by hMCs requires induction by IL-4, indicate that cell-specific regulation of LTC₄S expression dif-

fers among effector cell types. Such cell-specific regulation may explain the profound upregulation of LTC₄S in eosinophils, but not hMCs, in lung tissue biopsy specimens from patients with aspirin-sensitive asthma (48).

Although mouse bone marrow-derived MCs (BMMCs) can develop in vitro in response either to SCF with IL-6 and IL-10 (36) or to IL-3 alone (49), normal MC development in mice in vivo is SCF-dependent (50–52). IL-3-derived BMMCs express 5-LO in their nucleus at baseline (13) and preferentially generate cys-LTs over PGD₂ when activated via FcεRI. However, priming of these IL-3-driven BMMCs in vitro with SCF preferentially increases their capacity for PGD₂ generation by augmenting their expression of cPLA₂, PGHS-1, and PGD₂S (53). The apparently innate capacity for all tissue subpopulations of hMCs to generate PGD₂ may therefore reflect their SCF dependency in vivo. Our data confirm that SCF alone is sufficient to support a PGD₂-producing hMC population in vitro that is similar in eicosanoid product profile to hMCs from dispersed human skin (32). The previously reported capacity for IL-3 to upregulate cys-LT generation by SCF-driven mouse BMMCs (54) was associated with progressive increases in 5-LO and FLAP expression over 2 wk, followed at 4 to 5 wk by augmented LTC₄S expression concomitantly with a 12-fold increase in total BMMC numbers. In contrast, hMCs in our study did not increase in number during 5 d of cytokine priming, indicating that their cytokine-induced cys-LT biosynthetic capacity represented a phenotypic change, with a transition from a PGD₂-dominant profile of arachidonic acid metabolism to a nearly equivalent PGD₂/cys-LT profile reminiscent of dispersed lung or intestinal hMCs (33, 34).

Under resting conditions 5-LO localizes to the cytosol of neutrophils, but is in the nuclear euchromatin of alveolar macrophages, RBL cells, and mouse BMMCs cultured in WEHI medium (which contains murine IL-3 [55–58]). In each of these cells, 5-LO translocates to the nuclear envelope during activation-dependent LT generation. Nuclear import of 5-LO from the cytoplasm of neutrophils is associated with priming for subsequent enhanced calcium ionophore A23187-induced LT generation (58), possibly reflecting enhanced proximity to the other enzymes involved in LT biosynthesis. In our study, only a small minority of hMCs incubated with SCF alone or SCF plus IL-4 for 5 d showed nuclear staining for 5-LO. Priming with IL-3 or IL-5 increased the proportion of hMCs exhibiting nuclear staining for 5-LO at 5 d (as shown in a representative experiment; Fig. 8), an effect which did not require the presence of IL-4. Our study thus suggests that the priming effects of IL-3 and IL-5 for cys-LT production by hMCs includes the nuclear import of 5-LO, and may involve other mechanisms such as a slight upregulation of cPLA₂ (Fig. 7). Translocation of 5-LO from the cytosol to the nucleus has been proposed to explain IL-5-mediated priming of ionophore-stimulated LTC₄ production by human peripheral blood eosinophils (59).

An array of Th2 cytokines, including both IL-5 and IL-4, is strongly expressed through the influx of Th2 cells in

bronchial biopsy specimens from patients with asthma relative to individuals without asthma (60). IL-3 protein is localized to the bronchial epithelium in individuals with and without asthma (61). The increased numbers of hMCs in the bronchial mucosa of patients with newly diagnosed asthma (62) may reflect the comitogenic actions of Th2 cytokines on this SCF-dependent lineage. The fact that endobronchial allergen challenge elicits markedly increased quantities of cys-LTs in the bronchoalveolar lavage fluids of patients with asthma relative to control individuals with allergic rhinitis alone (41) may reflect disease-related phenotypic modifications of local hMCs induced by these same cytokines. Our study demonstrates that Th2 cytokines alter the profile of eicosanoids generated by mature hMCs, and it is the first to suggest a mechanistic basis for this phenotypic change. Furthermore, our findings suggest that hMCs, which depend on SCF for their normal development and survival, have a constitutive arachidonic acid phenotype that is characterized by PGD₂ generation predominating markedly over cys-LT generation. This arachidonic acid profile of PGD₂ >> cys-LT is substantially modified, with a profound increment in cys-LTs, by priming the hMCs with IL-4 to induce LTC₄S and with IL-3 or IL-5 to maintain 5-LO at the nucleus before FcεRI-mediated activation.

This work was supported by National Institutes of Health grants AI01305, AI31599, AI22531, and HL36110, and by a grant from the Hyde and Watson Foundation. Dr. Hsieh is the recipient of grants from Glaxo-Wellcome Pharmaceuticals.

Submitted: 25 May 2000

Revised: 20 November 2000

Accepted: 28 November 2000

References

1. Enerback, L. 1966. Mast cells in rat gastrointestinal mucosa. I. Effects of fixation. *Act. Pathol. Microbiol. Scand.* 66:289–302.
2. Nakano, T., T. Sonoda, C. Hayashi, A. Yamatodani, Y. Kanayama, T. Yamamura, H. Asai, T. Yonezawa, Y. Kitamura, and S.J. Galli. 1985. Fate of bone marrow-derived cultured mast cells after intracutaneous, intraperitoneal, and intravenous transfer into genetically mast cell-deficient *W/W^v* mice. Evidence that cultured mast cells can give rise to both connective tissue type and mucosal mast cells. *J. Exp. Med.* 162:1025–1043.
3. Schulman, E.S., A. Kagey-Sobotka, D.W. MacGlashan, Jr., N.F. Adkinson, Jr., S.P. Peters, R.P. Schleimer, and L.M. Lichtenstein. 1983. Heterogeneity of human mast cells. *J. Immunol.* 131:1936–1941.
4. Lewis, R.A., N.A. Soter, P.T. Diamond, K.F. Austen, J.A. Oates, and L.J. Roberts. 1982. Prostaglandin D₂ generation after activation of rat and human mast cells with anti-IgE. *J. Immunol.* 129:1627–1631.
5. MacGlashan, D.W., Jr., R.P. Schleimer, S.P. Peters, E.S. Schulman, G.K. Adams, III, H.H. Newball, and L.M. Lichtenstein. 1982. Generation of leukotrienes by purified lung mast cells. *J. Clin. Invest.* 70:747–751.
6. Clark, J.D., L.L. Lin, R.W. Kriz, C.S. Ramesha, L.A. Sultzman, A.Y. Lin, N. Milona, and J.L. Knopf. 1991. A novel arachidonic acid-selective cytosolic PLA₂ contains a Ca²⁺-

- dependent translocation domain with homology to PKC and GAP. *Cell*. 65:1043–1051.
7. De Witt, D.L., and W.L. Smith. 1988. Primary structure of prostaglandin G/H synthase from sheep vesicular gland determined from the complementary DNA sequence. *Proc. Natl. Acad. Sci. USA*. 85:1412–1416.
 8. O'Banion, M.K., V.D. Winn, and D.A. Young. 1992. cDNA cloning and functional activity of a glucocorticoid-regulated inflammatory cyclooxygenase. *Proc. Natl. Acad. Sci. USA*. 89:4888–4892.
 9. Urade, Y., M. Ujihara, Y. Horiguchi, M. Igarashi, A. Nagata, K. Ikai, and O. Hayaishi. 1990. Mast cells contain spleen-type prostaglandin D synthetase. *J. Biol. Chem.* 265:371–375.
 10. Wenzel, S.E., J.Y. Westcott, H.R. Smith, and G.L. Larsen. 1989. Spectrum of prostanoid release after bronchoalveolar allergen challenge in atopic asthmatics and in control groups: an alteration in the ratio of bronchoconstrictive to broncho-protective mediators. *Am. Rev. Respir. Dis.* 139:450–457.
 11. Sousa, A.R., R. Pfister, P.E. Christie, S.J. Lane, S.M. Nasser, M. Schmitz-Schumann, and T.H. Lee. 1997. Enhanced expression of cyclooxygenase isoenzyme 2 (COX-2) in asthmatic airways and its cellular distribution in aspirin-sensitive asthma. *Thorax*. 52:940–945.
 12. Matsuoka, T., M. Hirata, H. Tanaka, Y. Takahashi, T. Murata, K. Kabashima, Y. Sugimoto, T. Kobayashi, F. Ushikubi, Y. Aze, et al. 2000. Prostaglandin D₂ as a mediator of allergic asthma. *Science*. 287:2013–2017.
 13. Malavia, R., R. Malavia, and B.A. Jakschik. 1993. Reversible translocation of 5-lipoxygenase in mast cells upon IgE/antigen stimulation. *J. Biol. Chem.* 268:4939–4944.
 14. Dixon, R.A., R.E. Diehl, E. Opas, E. Rands, P.J. Vickers, J.F. Evans, J.W. Gillard, and D.K. Miller. 1990. Requirement of a 5-lipoxygenase-activating protein for leukotriene biosynthesis. *Nature*. 343:282–284.
 15. Reid, G.K., S. Kargman, P.J. Vickers, J.A. Mancini, C. Leveille, D. Ethier, D.K. Miller, J.W. Gillard, R.A. Dixon, and J.F. Evans. 1990. Correlation between expression of 5-lipoxygenase-activating protein, 5-lipoxygenase, and cellular leukotriene synthesis. *J. Biol. Chem.* 265:19818–19823.
 16. Evans, J.F., P. Dupuis, and A.W. Ford-Hutchinson. 1985. Purification and characterization of leukotriene A₄ hydrolase from rat neutrophils. *Biochim. Biophys. Acta*. 840:43–50.
 17. Nicholson, D.W., A. Ali, J.P. Vaillancourt, J.R. Calaycay, R.A. Mumford, R.J. Zamboni, and A.W. Ford-Hutchinson. 1993. Purification to homogeneity and the N-terminal sequence of human leukotriene C₄ synthase: a homodimeric glutathione S-transferase composed of 18-kDa subunits. *Proc. Natl. Acad. Sci. USA*. 90:2015–2019.
 18. Lam, B.K., J.F. Penrose, G.J. Freedman, and K.F. Austen. 1994. Expression cloning of a cDNA for human leukotriene C₄ synthase, a novel integral membrane protein conjugating reduced glutathione to leukotriene A₄. *Proc. Natl. Acad. Sci. USA*. 91:7663–7669.
 19. Welsch, D.J., D.P. Creely, S.D. Hauser, K.J. Mathis, G.G. Krivi, and P.C. Isakson. 1994. Molecular cloning and expression of human leukotriene C₄ synthase. *Proc. Natl. Acad. Sci. USA*. 91:9745–9749.
 20. Lam, B.K., W.F. Owen, K.F. Austen, and R.J. Soberman. 1989. The identification of a distinct export step following the biosynthesis of leukotriene C₄ by human eosinophils. *J. Biol. Chem.* 264:12885–12891.
 21. Anderson, M.E., R.D. Allison, and A. Meister. 1982. Interconversion of leukotrienes catalyzed by purified γ -glutamyl transpeptidase: concomitant formation of leukotriene D₄ and γ -glutamyl amino acids. *Proc. Natl. Acad. Sci. USA*. 79:1088–1091.
 22. Lee, C.W., R.A. Lewis, E.J. Corey, and K.F. Austen. 1983. Conversion of leukotriene D₄ to leukotriene E₄ by a dipeptidase released from the specific granules of human polymorphonuclear leukocytes. *Immunology*. 48:27–35.
 23. Lynch, K.R., G.P. O'Neill, Q. Liu, D.S. Im, N. Sawyer, K.M. Metters, N. Coulombe, M. Abramovitz, D.J. Figueroa, Z. Zeng, et al. 1999. Characterization of the human cysteinyl leukotriene cysLT1 receptor. *Nature*. 399:789–793.
 24. Heise, C.E., B.F. O'Dowd, D.J. Figueroa, N. Sawyer, T. Nguyen, D.S. Im, R. Stocco, J.N. Bellefeuille, M. Abramovitz, R. Cheng, et al. 2000. Characterization of the human cysteinyl leukotriene 2 (CysLT2) receptor. *J. Biol. Chem.* 275:30531–30536.
 25. Davidson, A.B., T.H. Lee, P.D. Scanlon, J. Solway, E.R. McFadden, Jr., R.H. Ingram, Jr., E.J. Corey, K.F. Austen, and J.M. Drazen. 1987. Bronchoconstrictor effects of leukotriene E₄ in normal and asthmatic subjects. *Am. Rev. Respir. Dis.* 135:333–337.
 26. Griffin, M., J.W. Weiss, A.G. Leitch, E.R. McFadden, Jr., E.J. Corey, K.F. Austen, and J.M. Drazen. 1983. Effect of leukotriene D₄ on the airways in asthma. *N. Engl. J. Med.* 308:436–439.
 27. Marom, Z., J.H. Shelhamer, M.K. Bach, D.R. Morton, and M. Kaliner. 1982. Slow-reacting substances, leukotrienes C₄ and D₄, increase the release of mucus from human airways in vitro. *Am. Rev. Respir. Dis.* 126:449–451.
 28. Laitinen, L.A., A. Laitinen, T. Haahtela, V. Vilkkka, B.W. Spur, and T.H. Lee. 1993. Leukotriene E₄ and granulocytic infiltration into asthmatic airways. *Lancet*. 341:989–990.
 29. Israel, E., J. Cohn, L. Dube, and J.M. Drazen. 1996. Effect of treatment with zileuton, a 5-lipoxygenase inhibitor, in patients with asthma. A randomized controlled trial. Zileuton Clinical Trial Group. *JAMA (J. Am. Med. Assoc.)*. 275:931–936.
 30. Israel E., E.F. Juniper, J.T. Callaghan, P.N. Mathur, M.M. Morris, A.R. Dowell, G.G. Enas, F.E. Hargreave, and J.M. Drazen. 1989. Effect of a leukotriene antagonist, LY171883, on cold air-induced bronchoconstriction in asthmatics. *Am. Rev. Respir. Dis.* 140:1348–1353.
 31. Massey, W.A. C.B. Guo, A.M. Dvorak, W.C. Hubbard, B.S. Bhagavan, V.L. Cohan, J.A. Warner, A. Kagey-Sobotka, and L.M. Lichtenstein. 1991. Human uterine mast cells: isolation, purification, characterization, ultrastructure, and pharmacology. *J. Immunol.* 147:1621–1627.
 32. Lawrence, I.D., J.A. Warner, V.L. Cohan, W.C. Hubbard, A. Kagey-Sobotka, and L.M. Lichtenstein. 1987. Purification and characterization of human skin mast cells: evidence for human mast cell heterogeneity. *J. Immunol.* 139:3062–3069.
 33. Peters, S.P., D.W. MacGlashan, Jr., E.S. Schulman, R.P. Schleimer, E.C. Hayes, J. Rokach, N.F. Adkinson, Jr., and L.M. Lichtenstein. 1984. Arachidonic acid metabolism in purified human lung mast cells. *J. Immunol.* 132:1972–1979.
 34. Fox, C.C., A.M. Dvorak, S.P. Peters, A. Kagey-Sobotka, and L.M. Lichtenstein. 1985. Isolation and characterization of human intestinal mucosal mast cells. *J. Immunol.* 135:483–491.
 35. Kirshenbaum, A.S., S.W. Kessler, J.P. Goff, and D.D. Metcalfe. 1991. Demonstration of the origin of human mast cells from CD34⁺ bone marrow progenitor cells. *J. Immunol.* 146:1410–1415.
 36. Yuan, Q., M.F. Gurish, D.S. Friend, K.F. Austen, and J.A.

- Boyce. 1998. Identification of a novel stem cell factor-dependent mast cell progenitor. *J. Immunol.* 161:5143–5146.
37. Ochi, H., W.M. Hirani, Q. Yuan, D. Friend, K.F. Austen, and J.A. Boyce. 1999. T helper cell type 2 cytokine-mediated comitogenic responses and CCR3 expression during differentiation of human mast cells in vitro. *J. Exp. Med.* 190:267–280.
 38. Toru, H., C. Ra, S. Nonoyama, K. Suzuki, J. Yata, and T. Nakahata. 1996. Induction of the high-affinity IgE receptor (Fcε RI) on human mast cells by IL-4. *Int. Immunol.* 8:1367–1373.
 39. Boyce, J.A., B.K. Lam, J.F. Penrose, D.S. Friend, S. Parsons, W.F. Owen, and K.F. Austen. 1996. Expression of LTC₄ synthase during the development of eosinophils in vitro from cord blood progenitors. *Blood.* 88:4338–4347.
 40. Yamaguchi, M., K. Sayama, K. Yano, C.S. Lantz, N. Noben-Trauth, C. Ra, J.J. Costa, and S.J. Galli. 1999. IgE enhances FcεRI receptor I expression and IgE-dependent release of histamine and lipid mediators from human umbilical cord blood-derived mast cells: synergistic effect of IL-4 and IgE on human mast cell Fcε receptor I expression and mediator release. *J. Immunol.* 162:5455–5465.
 41. Wenzel, S.E., G.L. Larsen, K. Johnston, N.F. Voelkel, and J.Y. Westcott. 1990. Elevated levels of leukotriene C₄ in bronchoalveolar lavage fluid from atopic asthmatics after endobronchial allergen challenge. *Am. Rev. Respir. Dis.* 142:112–119.
 42. Chomarat, P., and J. Banchereau. 1998. Interleukin-4 and interleukin-13: their similarities and discrepancies. *Int. Rev. Immunol.* 17:1–52.
 43. Penrose, J.F., J. Spector, M. Baldasaro, K. Xu, J. Boyce, J.P. Arm, K.F. Austen, and B.K. Lam. 1996. Molecular cloning of the gene for human leukotriene C₄ synthase. Organization, nucleotide sequence, and chromosomal localization to 5q35. *J. Biol. Chem.* 271:11356–11361.
 44. Marsh, D.G., J.D. Neely, D.R. Breazeale, B. Ghosh, L.R. Freidhoff, E. Ehrlich-Kautzky, C. Schou, G. Krishnaswamy, and T.H. Beaty. 1994. Linkage analysis of IL-4 and other chromosome 5q31.1 markers and total serum immunoglobulin E concentrations. *Science.* 264:1152–1156.
 45. Noguchi, E., M. Shibasaki, T. Arinami, K. Takeda, T. Maki, T. Miyamoto, T. Kawashima, K. Kobayashi, and H. Hamaguchi. 1997. Evidence for linkage between asthma/atopy in childhood and chromosome 5q31–q33 in a Japanese population. *Am. J. Respir. Crit. Care Med.* 156:1390–1393.
 46. Zhao, J., K.F. Austen, and B.K. Lam. 2000. Cell-specific transcription of leukotriene C₄ synthase involves a kruppel-like transcription factor and Sp-1. *J. Biol. Chem.* 275:8903–8910.
 47. Riddick, C.A., K.J. Serio, C.R. Hodulik, W.L. Ring, M.S. Regan, and T.D. Bigby. 1999. TGF-beta increases leukotriene C₄ synthase expression in the monocyte-like cell line, THP-1. *J. Immunol.* 162:1101–1107.
 48. Cowburn, A.S., K. Sladek, J. Soja, L. Adamek, E. Nizankowska, A. Szczeklik, B.K. Lam, J.F. Penrose, K.F. Austen, S.T. Holgate, and A.P. Sampson. 1998. Overexpression of leukotriene C₄ synthase in bronchial biopsies from patients with aspirin-intolerant asthma. *J. Clin. Invest.* 101:834–846.
 49. Ihle, J.N., J. Keller, S. Oroszlan, L.E. Henderson, T.D. Copeland, F. Fitch, M.B. Prystowsky, E. Goldwasser, J.W. Schrader, E. Palaszynski, et al. 1983. Biologic properties of homogeneous interleukin 3. Demonstration of WEHI-3 growth factor activity, mast cell growth factor activity, P cell-stimulating factor activity, colony-stimulating factor activity, and histamine-producing cell-stimulating factor activity. *J. Immunol.* 131:282–287.
 50. Kitamura, Y., S. Go, and K. Hatanaka. 1978. Decrease of mast cells in W/W^v mice and their increase by bone marrow transplantation. *Blood.* 52:447–452.
 51. Geissler, E.N., M.A. Ryan, and D.E. Housman. 1988. The dominant-white spotting (W) locus of the mouse encodes the *c-kit* proto-oncogene. *Cell.* 55:185–192.
 52. Huang, E., K. Nocka, D.R. Beier, T.Y. Chu, J. Buck, H.W. Lahm, D. Wellner, P. Leder, and P. Besmer. 1990. The hematopoietic growth factor KL is encoded by the *Sl* locus and is the ligand of the *c-kit* receptor, the gene product of the *W* locus. *Cell.* 63:225–233.
 53. Murakami, M., R. Matsumoto, Y. Urade, K.F. Austen, and J.P. Arm. 1995. *c-kit* ligand mediates increased expression of cytosolic phospholipase A₂, prostaglandin endoperoxide synthase 1, and hematopoietic prostaglandin D₂ synthase and increased IgE-dependent PGD₂ generation in immature mouse mast cells. *J. Biol. Chem.* 270:3239–3246.
 54. Murakami, M., K.F. Austen, C.O. Bingham, III, D.S. Friend, J.F. Penrose, and J.P. Arm. 1995. Interleukin-3 regulates development of the 5-lipoxygenase/leukotriene C₄ synthase pathway in mouse mast cells. *J. Biol. Chem.* 270:22653–22656.
 55. Brock, T.G., R.W. McNish, and M. Peters-Golden. 1995. Translocation and leukotriene synthetic capacity of nuclear 5-lipoxygenase in rat basophilic leukemia cells and alveolar macrophages. *J. Biol. Chem.* 270:21652–21658.
 56. Woods, J., M. Coffey, T. Brock, I. Singer, and M. Peters-Golden. 1995. 5-lipoxygenase is located in the euchromatin of the nucleus in resting human alveolar macrophages and translocates to the nuclear envelope upon cell activation. *J. Clin. Invest.* 95:2035–2046.
 57. Chen, X.S., T.A. Naumann, U. Kurre, N.A. Jenkins, N.G. Copeland, and C.D. Funk. 1995. cDNA cloning, expression, mutagenesis, intracellular localization, and gene chromosomal assignment of mouse 5-lipoxygenase. *J. Biol. Chem.* 270:17993–17999.
 58. Brock, T.G., R.W. McNish, M.B. Bailie, and M. Peters-Golden. 1997. Rapid import of cytosolic 5-lipoxygenase into the nucleus of neutrophils after in vivo recruitment and in vitro adherence. *J. Biol. Chem.* 272:8276–8280.
 59. Cowburn, A.S., S.T. Holgate, and A.P. Sampson. 1999. IL-5 increases expression of 5-lipoxygenase-activating protein and translocates 5-lipoxygenase to the nucleus in human blood eosinophils. *J. Immunol.* 163:456–465.
 60. Ying, S., M. Humbert, J. Barkans, C.J. Corrigan, R. Pfister, G. Menz, M. Larche, D.S. Robinson, S.R. Durham, and A.B. Kay. 1997. Expression of IL-4 and IL-5 mRNA and protein product by CD4⁺ and CD8⁺ T cells, eosinophils, and mast cells in bronchial biopsies obtained from atopic and non-atopic (intrinsic) asthmatics. *J. Immunol.* 158:3539–3544.
 61. Woolley, K.L., E. Adelroth, M.J. Woolley, I. Ramis, J.S. Abrams, M. Jordana, and P.M. O'Byrne. 1996. Interleukin-3 in bronchial biopsies from nonasthmatics and patients with mild and allergen-induced asthma. *Am. J. Respir. Crit. Care Med.* 153:350–355.
 62. Laitinen, L.A., A. Laitinen, and T. Haahtela. 1993. Airway mucosal inflammation even in patients with newly diagnosed asthma. *Am. Rev. Respir. Dis.* 147:697–704.