

Lipoxin A₄ Modulates Transmigration of Human Neutrophils across Intestinal Epithelial Monolayers

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Abstract

Neutrophil (PMN) migration across intestinal epithelial barriers, such as occurs in many disease states, results in modifications in epithelial barrier. Here, we investigated the impact of lipoxin A₄ (LXA₄), an eicosanoid with counterregulatory inflammatory roles, on PMN migration across cultured monolayers of the human intestinal epithelial cell line T₈₄. Transepithelial migration of PMN was assessed in the apical-to-basolateral direction and in the basolateral-to-apical direction. In the apical-to-basolateral direction, preexposure of PMN to LXA₄ (10 nM, 15 min) stimulated an 87±5% increase in transepithelial migration of PMN as determined by a PMN myeloperoxidase assay. The LXA₄-elicited effect on transmigration was present throughout the 2-h assay period and was not secondary to LXA₄ effects on epithelial monolayer integrity as judged by measurement of transepithelial resistance. PMN migration in the basolateral-to-apical direction was modulated by LXA₄ with a comparable time- and concentration-dependence to that in the apical-to-basolateral direction. However, qualitative differences in how LXA₄ modulates transmigration in the two opposing directions were observed. In the basolateral-to-apical direction, preexposure of PMN to LXA₄ (10 nM, 15 min) diminished PMN transepithelial migration by 33±4%. Structure-function studies revealed that LXA₄ and 11-*trans*-LXA₄ (50% of LXA₄ effect), but not LXB₄, inhibited basolateral-to-apical PMN transmigration. The action of LXA₄ was not sensitive to inhibitors of cyclooxygenase or specific leukotriene biosynthesis, but was sensitive to staurosporine, a protein kinase C inhibitor. These results suggest that migration of PMN across epithelia in the physiological direction may be qualitatively different following PMN exposure to eicosanoids. We propose that such retention of PMN at this specific anatomic location may serve an important role in mucosal defense. (*J. Clin. Invest.* 1993. 92:75–82.) Key words: inflammation • intestinal disease • eicosanoid • arachidonic acid

Introduction

PMN migration across intestinal epithelia is the hallmark of active intestinal inflammation and occurs in such disease states as ulcerative colitis, Crohn's disease and infectious enterocolitis (1, 2). Transepithelial migration of PMN is particularly evident in the intestinal crypt and eventuates in crypt abscess

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Received for publication 22 September 1992 and in revised form 3 February 1993.

J. Clin. Invest.

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0021-9738/93/07/75/08 \$2.00

Volume 92, July 1993, 75–82

formation, a characteristic of severe inflammatory disease (1, 2). In patients with inflammatory bowel disease, the degree of PMN transepithelial migration, assessed quantitatively, has been shown to correlate with patients symptoms, as well as with the degree of intestinal epithelial barrier dysfunction (3). Studies of human mucosa in such diseases suggest that PMN transepithelial migration predates focal breakdown of the epithelial surface (1, 2), and that defective epithelial barrier function also predates structural discontinuities in the mucosa (4).

An early and crucial step in the acute inflammatory response is attachment of neutrophils (PMN) to endothelial surfaces and subsequent emigration from the vasculature (1, 2). However, during inflammatory episodes in organs lined by columnar epithelia, subsequent PMN migration across the epithelial surface occurs (1, 2). While substantial progress has been made in the understanding of PMN-endothelial interactions (5–9), relatively limited information is available concerning PMN-epithelial interactions (10–15). We have previously modelled the event of PMN transepithelial migration using human PMN and cultured, human-derived, intestinal epithelial monolayers derived from the cell line T₈₄ (reviewed in reference 16). Such monolayers are composed of columnar epithelial cells with features similar to those of natural crypt epithelia (17, 18), the site at which the bulk of PMN transepithelial migration occurs in a variety of active inflammatory intestinal diseases (1, 2).

Previous studies using this epithelium as a model for examination of PMN-intestinal epithelial interactions indicate that PMN transmigration elicits a reversible decrease in transepithelial resistance caused by impalement of intercellular tight junctions (11), and requires the PMN β_2 -integrin CD11b/CD18 (14, 15). While we have shown that PMN transmigration is quantitatively more substantial in the physiological (basolateral-to-apical) direction (14), qualitative differences in transepithelial migration, relating to the direction of transmigration, have generally not been observed (11, 12, 14) (with the exception of IFN- γ -modulated PMN transepithelial migration [19]).

Lipoxins are lipoxygenase-derived, biologically active eicosanoids produced by PMN, platelets, eosinophils, and macrophages (20, 21). These compounds have been shown to elicit selective counterregulatory responses in human PMN in vitro, including the inhibition of leukotriene B₄ (LTB₄) and FMLP-stimulated chemotactic responses (22, 23), blocking of Ca²⁺ mobilization (24), and inhibition of LTD₄-induced adhesion to mesangial cells (25). In vivo, lipoxins are potent inflammatory mediators which act to inhibit leukocyte migration (26), decrease LTD₄-induced vasoconstriction (27) and modulate LTD₄-induced airway obstruction (28).

Here we examine the impact of PMN exposure to lipoxin A₄ (LXA₄)¹ on subsequent transepithelial migration of human

1. Abbreviations used in this paper: LXA₄, lipoxin A₄; MPO, myeloperoxidase; PKC, protein kinase C; PMN CE, PMN cell equivalents.

PMN across monolayers of a cryptlike human intestinal epithelial cell line. Previous exposure of PMN to nanomolar concentrations of LXA₄ substantially alters subsequent PMN transepithelial migration. The action of LXA₄ was found to be specific for PMN, showed a similar time and dose dependency, and the effect was dependent on the direction of PMN transepithelial migration.

Methods

Lipoxins. Synthetic LXA₄, LXB₄, and 11-*trans*-LXA₄ were obtained from Cascade Biochem Ltd. (Berkshire, UK). Concentrations were determined from extinction coefficients as described previously (28). All eicosanoid stock solutions were stored at -70°C in methanol (American Scientific Products Div. American Hospital Supply Corp., McGaw, IL). Eicosanoids were diluted in modified HBSS to a concentration of 1 μM before all experiments. PMN or T₈₄ monolayers were exposed to lipoxins at indicated concentrations and allowed to incubate at 37°C for the indicated period of time. Vehicle controls consisted of dilutions of the solvent (ethanol) equivalent to the highest concentration of lipoxin used in any given experiment (0.01%).

Cell culture. Approximately 350 epithelial monolayers were used for these studies. T₈₄ intestinal epithelial cells (passages 70–95) were grown and maintained as confluent monolayers on collagen-coated permeable supports as previously described in detail (11, 12). Monolayers were grown on 0.33 cm² ring-supported polycarbonate filters (Costar Corp., Cambridge, MA) and used 6–14 d after plating as described previously (16). Transepithelial resistance to passive ion flow was measured as previously described (14–16). Inverted monolayers, used to study transmigration of PMN in the basolateral-to-apical direction, were constructed as described before (14, 16).

Transmigration assay. The PMN transepithelial migration assay has been previously detailed (11, 12, 14, 15). Briefly, human PMN were isolated from normal human volunteers and suspended in modified HBSS (without Ca²⁺ and Mg²⁺, with 10 mM Hepes, pH 7.4, Sigma Immunochemicals, St. Louis, MO) at a concentration of 5 × 10⁷/ml. Before addition of PMN, T₈₄ monolayers were extensively rinsed in HBSS to remove residual serum components. Transmigration assays were performed by the addition of PMN (40 μl) to HBSS (160 μl) in the upper chambers after chemoattractant (1 μM FMLP in HBSS) was added to the opposing (lower) chambers. Unless otherwise indicated, PMN were not washed free of LXA₄ before addition to monolayers, and therefore, a fivefold dilution of lipoxin was present during the transmigration assay. For apical-to-basolateral transmigration experiments, PMN (2 × 10⁶) were added at time 0. We have previously shown that transmigration in the basolateral-to-apical direction, while qualitatively similar, is substantially more efficient than in the apical-to-basolateral direction (14). Therefore, fivefold fewer PMN (4 × 10⁵) were added when transmigration proceeded in the basolateral-to-apical direction so that baseline transmigration signals be approximately equivalent in both directions (14). Transmigration was allowed to proceed for 120 min, unless otherwise noted. All PMN transepithelial migration experiments were performed in a 37°C room to ensure that epithelial monolayers, solutions, plasticware, etc., were maintained at uniform 37°C temperature.

When used, inhibitors to cyclooxygenase (indomethacin; Sigma Immunochemicals), leukotriene biosynthesis (MK886; a kind gift from Merck Frosst, Quebec, Canada), G-proteins (pertussis toxin, Calbiochem, San Diego, CA), or protein kinase C (H7, Sigma Immunochemicals; and staurosporine, Sigma Immunochemicals) were preincubated with PMN at indicated concentrations for 15 min at 37°C. Inhibitors were washed free from PMN by two washes with HBSS. PMN were subsequently exposed to LXA₄ (10 nM) and PMN transepithelial migration was assessed as described above in the apical-to-basolateral direction.

Transmigration was quantitated by assaying for the PMN azurophilic granule marker myeloperoxidase (MPO) as described previously (14). After each transmigration assay, nonadherent PMN were extensively washed from the surface of the monolayer, and PMN cell equivalents (PMN CE), estimated from a standard curve, were assessed as the number of PMNs associated with the monolayer, the number that had completely traversed the monolayer (i.e., across the monolayer into the reservoir bath), as well as the total number of transmigrating PMN (the sum of monolayer and reservoir-associated PMN).

Data presentation. Individual experiments were performed using large numbers of uniform groups of monolayers and PMN from individual blood donors on individual days. PMN isolation was restricted to five different blood donors (repetitive donations) over the course of these studies. Myeloperoxidase assay data were compared by two-factor ANOVA or by comparison of means using Student's *t* test. PMN transmigration results are represented as PMN CE derived from a daily standard PMN dilution curve. Monolayer-associated PMN are represented as the number of PMN CE per monolayer and reservoir-associated PMN (i.e., PMN that had completely traversed the monolayer into the lower chamber) are represented as the number of PMN CE per milliliter (total volume of 1 ml). Values are expressed as the mean and SEM of *n* experiments.

Results

LXA₄ exposure to T₈₄ epithelial monolayers does not alter subsequent FMLP-induced PMN transmigration. PMN's can be induced to transmigrate across T₈₄ epithelial monolayers in response to a transepithelial gradient of the chemotactic peptide FMLP (1 μM) (11, 14). To determine whether LXA₄ exposure to T₈₄ intestinal epithelial cells influenced subsequent PMN transmigration, epithelial cell monolayers were incubated with LXA₄ at a concentration 10 nM for 15 min at 37°C (conditions which elicit significant effects when PMN's are preexposed to LXA₄, see below), with and without removal of LXA₄ from monolayers, followed by addition of untreated PMNs under chemotactic conditions. In these experiments, PMN transmigration across T₈₄ monolayers exposed to LXA₄ did not differ from vehicle control (14.8 ± 1.4 vs 15.7 ± 1.8 × 10⁴ PMN CE/ml for control and LXA₄-exposed monolayers, *n* = 6 each, NS). Removal of LXA₄ from monolayers by washing three times with HBSS before addition of PMN had no apparent effect on the total number of transmigrating PMN (14.3 ± 1.1 × 10⁴ PMN CE/ml, *n* = 6, NS compared to either control or LXA₄-exposed monolayers).

In addition, exposure of intestinal epithelial cells to LXA₄ did not significantly influence the integrity of T₈₄ epithelial monolayers. To examine this, transepithelial resistance to passive ion flow was assessed before and after addition of 10 nM LXA₄ to T₈₄ intestinal epithelial monolayers for 2 h (simulated conditions for entire transmigration assay period). During this period, transepithelial resistance did not significantly decrease after addition of LXA₄ (baseline resistance 1,255 ± 56 Ω · cm² and 1,089 ± 108 Ω · cm² after 2 h, *n* = 8, NS). These results suggest that monolayer integrity, as assessed by transepithelial resistance, was not affected by LXA₄ treatment and that epithelial preexposure to LXA₄ has no subsequent effect on FMLP-induced PMN transmigration.

LXA₄ does not stimulate transmigration. To investigate whether LXA₄ could serve to stimulate PMN transmigration in this assay system, dilutions of LXA₄ in the range of 0.01–10 nM were placed in the lower chamber of transmigration wells. Untreated PMN's were added to the upper chamber and assessed for chemotactic capacity toward LXA₄ in the apical-to-

basolateral direction. LXA₄ was no more effective than HBSS in promoting PMN transmigration; compared to FMLP (1 μM), PMN migration toward LXA₄ resulted in a total of 6±2.1, 9±3.6, 6±2.4, and 12±1.4% of FMLP-induced PMN transmigration for 0.01, 0.1, 1.0, and 10 nM LXA₄, respectively. In the absence of a chemotactic gradient (HBSS), 10±2.9% of FMLP-induced transmigration occurred. These results indicate that LXA₄, in the concentrations tested, did not stimulate PMN transepithelial migration.

Preexposure of PMN to LXA₄ enhances FMLP-induced PMN transmigration in the apical-to-basolateral direction. To determine if PMN exposure to LXA₄ alters subsequent FMLP-induced transmigration, PMN were incubated with 10 nM LXA₄ for 15 min, then added directly to the apical surface of T₈₄ epithelial monolayers, and subsequently assessed for their ability to traverse T₈₄ epithelial monolayers using a myeloperoxidase assay (14). PMN preexposure to LXA₄ resulted in significantly increased PMN transepithelial migration in the apical-to-basolateral direction (Fig. 1). Increased PMN migration was evident in both monolayer-associated PMN numbers (2.98±0.57 vs 6.93±1.77 × 10⁴ PMN CE/monolayer for vehicle control and LXA₄-exposed PMN, respectively, *P* < .001), as well as the number of PMN that completely traversed the epithelial monolayer (6.61±0.50 vs 11.02±2.91 × 10⁴ PMN CE/ml for vehicle control and LXA₄-exposed, respectively, *P* < 0.01), resulting in a nearly twofold increase in the total number of transmigrating PMN (9.58±1.05 × 10⁴ PMN CE/ml for vehicle control and 17.95±2.15 × 10⁴ PMN CE/ml for LXA₄ preexposed PMN, *P* < 0.01). As reported previously (14), examination of 1 μm T₈₄ epithelial monolayer sections revealed that PMNs are only rarely associated with the apical epithelial surface and the majority of monolayer-associated PMN are found subjunctionally, indicative of transmigration. Therefore, monolayer-associated PMN in this apical-to-basolateral assay are considered transmigrated across the tight junction,

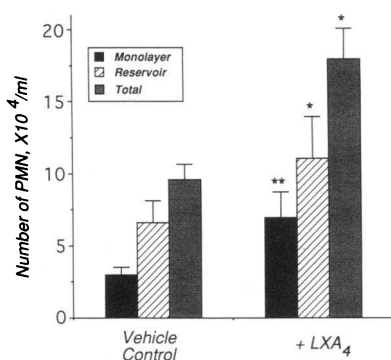


Figure 1. LXA₄ enhances PMN transepithelial migration in the apical-to-basolateral direction. PMN (5 × 10⁷/ml) were preincubated with 10 nM LXA₄ for 15 min at 37°C and layered on the apical surface of washed T₈₄ epithelial monolayers at a density of 2 × 10⁶/monolayer. PMN were driven to

transmigrate basolaterally under the influence of a 1-μM gradient of FMLP. Shown here are the results obtained from harvesting the PMN-specific enzyme MPO from washed monolayers, lower reservoirs and total MPO activity after 120 min, relative to a known standard number of PMN. Since tight junctions are the rate limiting barrier to passive paracellular permeation, transmigration is defined as movement of PMN across the tight junction. Since monolayer-associated PMN were largely below the tight junction (see Results), total transmigration in the apical-to-basolateral direction equals the sum of PMN in the opposite reservoir plus monolayer PMN. Data are pooled from nine individual monolayers in each condition, and results are expressed as the mean and SEM. Asterix indicates statistically significant compared to vehicle control (**P* < 0.01; ***P* < 0.001).

tion, the rate-limiting barrier in PMN transepithelial migration (14).

To further characterize this transmigratory event, PMNs were preexposed to LXA₄ (10 nM) for various periods of time and subsequently assessed for their ability to transmigrate across T₈₄ epithelial monolayers in the apical-to-basolateral direction (Fig. 2). Results in Fig. 2 A show that preexposure of PMNs to LXA₄ resulted in increased total PMN transmigration after a LXA₄ preexposure period of 5–30 min. (compared to vehicle controls, for PMNs preexposed to 10 nM LXA₄, transmigration increased by 50, 68, and 51% at 5, 15, and 30 min exposure times, respectively, all *P* < 0.025). Transmigration had returned to vehicle control values by 45 and 60 min of PMN preexposure to LXA₄. Preexposure of PMN to LXA₄ was found to be a necessary prerequisite for LXA₄ action on stimulating PMN transmigration. Indeed, exposure of PMNs to 10 nM LXA₄ immediately before their addition to epithelial monolayers (i.e., 0 min preexposure) resulted in no effect on subsequent FMLP-induced PMN migration (Fig. 2 A,

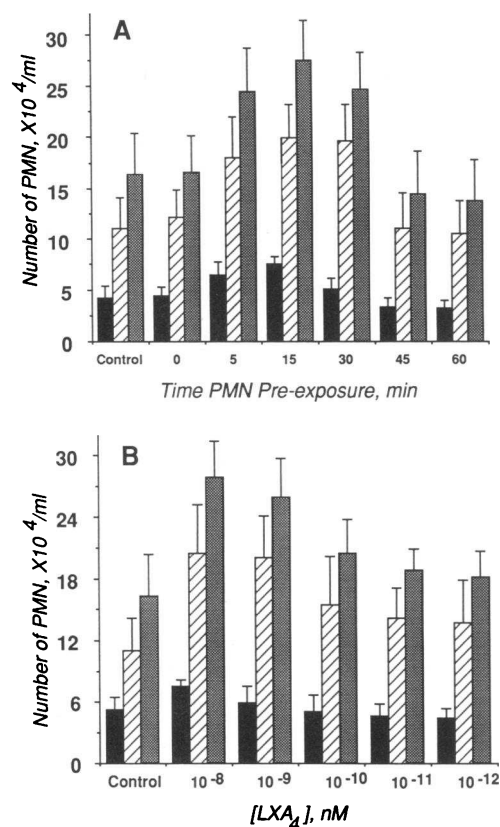


Figure 2. Preexposure time and concentration dependence of lipoxin A₄ on enhanced PMN transepithelial migration in the apical-to-basolateral direction. PMN (5 × 10⁷/ml) were preincubated with 10 nM LXA₄ for various periods of time in the range of 0–60 min at 37°C (A) or preincubated with various indicated concentrations of LXA₄ for 15 min at 37°C (B) and layered on the apical surface of washed T₈₄ epithelial monolayers at a density of 2 × 10⁶/monolayer. PMN were driven to transmigrate basolaterally under the influence of a 1 μM gradient of FMLP. Shown here are the results obtained from harvesting the PMN-specific enzyme MPO from washed monolayers, lower reservoirs, and total MPO activity after 120 min, relative to a known standard number of PMN. Data are pooled from 7–10 individual monolayers in each condition, and results are expressed as the mean and SEM. ■, Monolayer; ▨, reservoir; ■, total.

16.34±4.07 vs 16.61±3.56 × 10⁴ total PMN CE/ml for vehicle control and LXA₄ preexposure for 0 min, respectively, NS). The LXA₄ preexposure time-dependent enhancement of subsequent neutrophil transmigration was largely caused by reservoir-associated PMN (11.06±3.05 vs 18.02±3.35, 19.96±3.18, 19.64±3.54 × 10⁴ PMN CE/ml for vehicle control and PMN LXA₄ preexposure times of 5, 15, and 30 min, respectively, two-factor ANOVA *P* < 0.01). However, a significant increase in the number of monolayer-associated PMN occurred at 15 min of LXA₄ preexposure (4.17±1.17 for vehicle control vs 7.55±0.71 × 10⁴ PMN CE/monolayer for PMNs exposed to 10 nM LXA₄, *P* < 0.01).

The concentration dependence of LXA₄ preexposure to PMN and subsequent PMN transepithelial migration in the apical-to-basolateral direction is shown in Fig. 2 *B*. Preexposure of PMN to LXA₄ concentrations in the range of 1.0 pM–10 nM for 15 min at 37°C elicited increased PMN transmigration at doses of 0.1, 1.0, and 10 nM final concentrations. Similar to the time course data presented above, LXA₄-elicited stimulation of PMN transmigration was manifest as an increase in the number of PMN in lower reservoirs (11.06±3.05 vs 20.38±4.83, 19.96±4.83, 15.43±4.65, 14.11±3.01, and 13.71±4.14 × 10⁴ PMN CE/ml for vehicle control, and PMN LXA₄ preexposure doses of 10, 1, 0.1, 0.01, and 0.001 nM, respectively, for 15 min, 37°C, two-factor ANOVA, *P* < 0.025).

To determine whether the stimulatory action of LXA₄ was present throughout the incubation period, PMNs were preexposed to LXA₄ (10 nM, 15 min), layered on the apical surface of T₈₄ monolayers and driven to transmigrate basolaterally. Monolayers were harvested at various time points during transmigration and assayed for PMN by myeloperoxidase content. As shown in Fig. 3, the stimulatory effect of LXA₄ on PMN migration in the apical-to-basolateral direction was present by

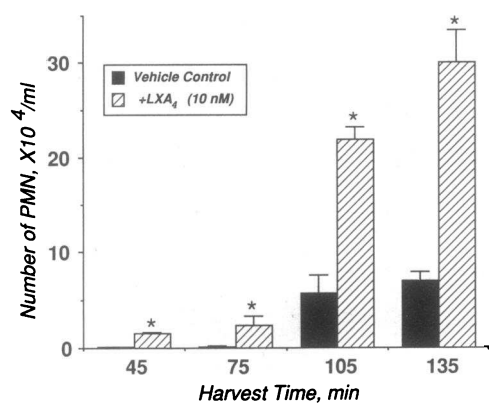


Figure 3. Lipoxin A₄ enhancement of PMN transepithelial migration in the apical-to-basolateral direction is present throughout the assay period. PMN (5 × 10⁷/ml) were preincubated with 10 nM LXA₄ for 15 min at 37°C and layered on the apical surface of washed T₈₄ epithelial monolayers at a density of 2 × 10⁶/monolayer. PMN were driven to transmigrate basolaterally under the influence of a 1-μM gradient of FMLP. Monolayers were harvested at the indicated periods of time. Shown here are the results obtained from assaying the PMN-specific enzyme MPO, relative to a known standard number of PMN. Total MPO activity (including reservoir- and monolayer-associated MPO activity) is indicated. Data are pooled from six individual monolayers in each condition, and results are expressed as the mean and SEM. Asterisk indicates statistically significant compared to vehicle control (*P* < 0.001).

45 min after addition of PMN (0.06±0.04 vs 1.51±0.12 × 10⁴ PMN CE/ml for vehicle control and PMN exposed to LXA₄, respectively, *P* < 0.05), and was maintained throughout the 135-min experimental period (two-factor ANOVA, *P* < 0.01).

To assess whether preexposure of PMN to LXA₄ is reversible, PMN were incubated with 10 nM LXA₄ for 15 min, washed twice in Ca²⁺ and Mg²⁺-free HBSS, and assessed for their ability to migrate across monolayers of T₈₄ epithelial cells in the apical-to-basolateral direction. Here, PMNs exposed to LXA₄ did not differ from control in their ability to migrate across T₈₄ epithelial monolayers (14.1±0.4 vs 14.5±0.3 × 10⁴ PMN CE/ml for control and LXA₄ exposure followed by washout, respectively, *n* = 6 each, NS). In the presence of LXA₄, a total of 18.6±1.0 × 10⁴ PMN CE/ml migrated (*n* = 6, *P* < 0.025 compared to control and washout control), suggesting that LXA₄-induced enhancement of PMN migration in the apical-to-basolateral direction requires the presence of LXA₄.

Finally, we determined whether PMN-conditioned LXA₄ and epithelial-conditioned LXA₄ maintained its ability to enhance PMN transmigration in the apical-to-basolateral direction. Samples of LXA₄ (10 nM) were incubated with either PMN or T₈₄ epithelial cells for 15 or 45 min. Supernatants were harvested and subsequently exposed to PMN for 15 min and added to the apical surface of T₈₄ monolayers under transmigration conditions (1 μM FMLP transepithelial gradient) for 2 h at 37°C. Compared to PMN preexposed to HBSS (11.3±2.2 × 10⁴ total PMN CE/ml), PMN preexposed to PMN-conditioned LXA₄ (15 min) resulted in a total PMN migration 18.0±2.1 × 10⁴ PMN CE/ml (*n* = 3, *P* < 0.05 compared to control). PMN preexposed to epithelial-conditioned LXA₄ (15 min) resulted in a total PMN migration 16.8±3.3 × 10⁴ PMN CE/ml (*n* = 3, *P* < 0.05 compared to control). Supernatants from PMN-conditioned LXA₄ (45 min) were not effective in enhancing PMN transmigration in the apical-to-basolateral direction (12.36±3.1 × 10⁴ total PMN CE/ml compared to HBSS control of 14.3±3.2 × 10⁴ total PMN CE/ml, *n* = 3, *P* = NS). These results suggest that enhancement of PMN migration in the apical-to-basolateral direction involves a step that is subsequent to PMN preincubation with LXA₄.

PMN preexposure to LXA₄ decreases FMLP-induced PMN transmigration in the basolateral-to-apical direction. We have recently reported that quantitative as well as qualitative differences can exist in PMN transepithelial migration depending on the direction of migration (19). To investigate the effect of LXA₄ on the polarity of transmigration, we prepared inverted monolayers (which permit basolateral-to-apically directed transmigration) to assess whether PMN preexposure to LXA₄ exhibited similar effects as shown above on subsequent PMN transmigration. Results in Fig. 4 show that preexposure of PMN to LXA₄ (10 nM) for 15 min markedly decreased PMN transmigration in the basolateral-to-apical direction. Unlike the results found in the apical-to-basolateral direction, transmigration of PMNs in this physiologically relevant direction was significantly decreased compared to vehicle controls (28.02±3.08 vs 18.77±1.48 × 10⁴ PMN/ml for control and PMNs preexposed to 10 nM LXA₄ for 15 min, respectively, *P* < 0.01, Fig. 4). Transmigration in the basolateral-to-apical direction resulted in no significant difference in the number of monolayer-associated PMNs after preexposure to LXA₄ (Fig. 4, 2.01±0.20 vs 2.00±0.31 for control and PMN exposed to LXA₄, respectively, *P* = NS). This polarized action of LXA₄ was confirmed by performing parallel apical-to-basolateral and

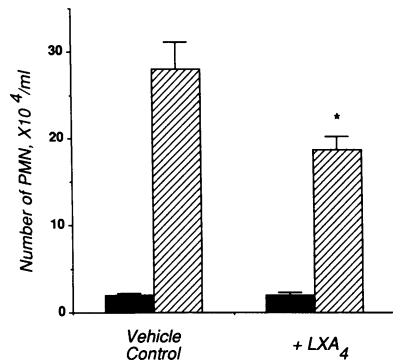


Figure 4. Lipoxin A₄ decreases PMN transepithelial migration in the physiologically relevant basolateral-to-apical direction. PMN ($1 \times 10^7/\text{ml}$) were preincubated with 10 nM LXA₄ for 15 min at 37°C and layered on the basolateral surface of washed T₈₄ epithelial monolayers (i.e., inverted monolayers) at a

density of $4 \times 10^5/\text{monolayer}$. PMN were driven to transmigrate apically under the influence of a $1\text{-}\mu\text{M}$ gradient of FMLP. Shown here are the results obtained from harvesting the PMN-specific enzyme MPO from lower reservoirs and washed monolayers after 120 min, relative to a known standard number of PMN. Since tight junctions are the rate limiting barrier to passive paracellular permeation, transmigration is defined as movement of PMN across the tight junction. Since monolayer-associated PMN were largely below the tight junction (see Results), total transmigration in the basolateral-to-apical direction equates with PMN in the opposite reservoir only. Data are pooled from nine individual monolayers in each condition, and results are expressed as the mean and SEM. Asterix indicates statistically significant compared to vehicle control ($P < 0.01$). ■, Monolayer; □, reservoir.

basolateral-to-apical transmigration experiments using T₈₄ cells from the same plating and same passage and using PMN from the same donors on three separate occasions.

A time course of LXA₄ preexposure to PMNs was next performed for basolateral-to-apical directed migration. The results revealed that, similar to the apical-to-basolateral direction, decreased transepithelial migration was present at 15 min of PMN preexposure to 10 nM LXA₄ (11.07 ± 1.83 for control vs $6.29 \pm 1.21 \times 10^4$ PMN/ml, $P < 0.01$). No differences in the number of monolayer-associated PMN were present at any period of LXA₄ exposure (data not shown). Dose-response experiments (all 15 min preexposure, Fig. 5) revealed that preexposure of PMN to 10 and 1 nM LXA₄ resulted in a significantly reduced number of transmigrating PMN in the basolateral-to-apical direction ($11.07 \pm 1.83 \times 10^4$ PMN/ml for control samples vs 6.29 ± 1.21 and $6.99 \pm 1.33 \times 10^4$ PMN/ml after preexposure to 10 and 1 nM LXA₄, respectively, both $P < 0.025$). Again, this diminished trans migratory response in the basolateral-to-apical direction was associated with reservoir-associated PMN only, with no apparent effect on the number of monolayer-associated PMN.

We also determined whether PMN-conditioned LXA₄ or epithelial-conditioned LXA₄ were effective in decreasing PMN transmigration in the basolateral-to-apical direction. Similar to our results in the apical-to-basolateral direction (see above), PMN preexposed to either PMN-conditioned LXA₄ (8.07 ± 1.63 vs buffer control $13.18 \pm 1.91 \times 10^4$ PMN/ml, $n = 4$, $P < 0.025$) or epithelial-conditioned LXA₄ (9.01 ± 1.76 compared to buffer control of $14.23 \pm 2.06 \times 10^4$ PMN/ml, $n = 4$, $P < 0.04$) maintained activity that decreased PMN transepithelial migration in the basolateral-to-apical direction.

Preexposure of PMN to structurally related lipoxins. To investigate the specificity of LXA₄ causing decreased transmigration in the physiological direction, we also examined the effects of PMN exposure LXB₄ and 11-*trans*-LXA₄ (Fig. 6).

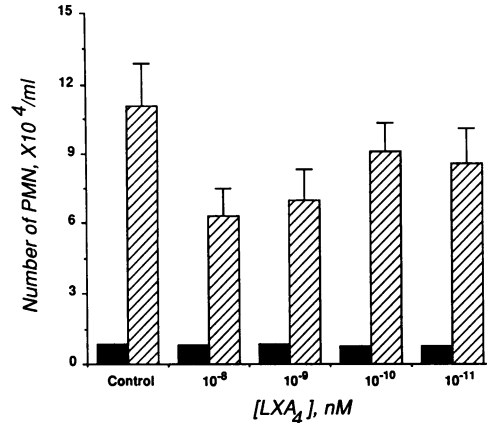


Figure 5. Concentration dependence of lipoxin A₄ on decreased PMN transepithelial migration in the basolateral-to-apical direction. PMN ($1 \times 10^7/\text{ml}$) were preincubated with various indicated concentrations of LXA₄ for 15 min at 37°C and layered on the basolateral surface of washed T₈₄ epithelial monolayers at a density of $4 \times 10^5/\text{monolayer}$. PMN were driven to transmigrate basolaterally under the influence of a $1 \mu\text{M}$ gradient of FMLP. Shown here are the results obtained from harvesting the PMN-specific enzyme MPO from lower reservoirs and washed monolayers after 120 min, relative to a known standard number of PMN. Data are pooled from 9–12 individual monolayers in each condition, and results are expressed as the mean and SEM. ■, Monolayer; □, reservoir.

PMN's were preincubated with these compounds using conditions as described above (10 nM, 15 min, 37°C) and layered on T₈₄ monolayers (physiologically oriented) under chemotactic conditions ($1 \mu\text{M}$ FMLP in lower reservoir). Preexposure of PMNs to 10 nM LXB₄, 11-*trans*-LXA₄ produced a $7 \pm 4\%$ ($P = \text{NS}$ compared to vehicle control) and $16 \pm 6\%$ ($P < 0.05$) inhibition of PMN transmigration, respectively, while LXA₄

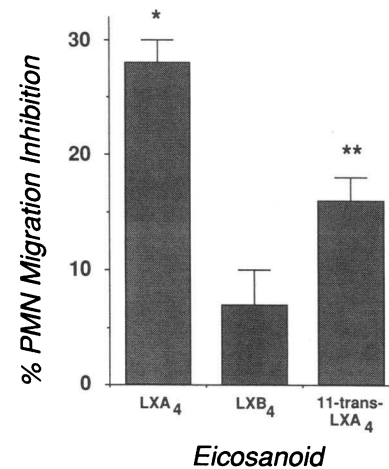


Figure 6. Comparison of lipoxin A₄ structurally related compounds on decreased PMN transepithelial migration in the basolateral-to-apical direction. PMN ($1 \times 10^7/\text{ml}$) were preincubated with 10 nM LXA₄, LXB₄, or 11-*trans*-LXA₄ for 15 min at 37°C and layered on the basolateral surface of washed T₈₄ epithelial monolayers (i.e., inverted monolayers) at a density of 4

$\times 10^5/\text{monolayer}$. PMN were driven to transmigrate apically under the influence of a $1 \mu\text{M}$ gradient of FMLP. Shown here are the results obtained from harvesting the PMN-specific enzyme MPO after 120 min, relative to a known standard number of PMN. Total MPO activity (including reservoir- and monolayer-associated MPO activity) is expressed as the percent PMN migration inhibition. Data are pooled from seven individual monolayers in each condition, and results are expressed as the mean and SEM. Asterix indicates statistically significant compared to vehicle control (* $P < 0.01$; ** $P < 0.05$).

inhibited migration by $28 \pm 4\%$ ($P < 0.01$). These observations suggest structural specificity for LXA_4 .

Effect of inhibitors on LXA_4 -elicited enhancement of PMN transepithelial migration in the apical-to-basolateral direction. To determine whether LXA_4 -induced modulation of PMN transmigration could be pharmacologically altered, a series of experiments were done in which PMN were exposed to specific inhibitors, washed free of inhibitor and subsequently assayed for the LXA_4 effect on PMN transepithelial migration in the apical-to-basolateral direction.

Preexposure of PMN to indomethacin ($50 \mu\text{M}$, 15 min, 37°C), a cyclooxygenase inhibitor (30), did not effect baseline PMN transmigration in the presence of a transepithelial gradient of FMLP ($109 \pm 13\%$ vehicle control, $n = 6$, $P = \text{NS}$ compared to untreated control). Likewise, preexposure of PMN to indomethacin followed by exposure to LXA_4 (10 nM) did not alter the LXA_4 -elicited increase in FMLP-driven PMN transmigration in the apical-to-basolateral direction ($61 \pm 11\%$ increase vs $54 \pm 7\%$ increase over control for LXA_4 -treated PMN with and without indomethacin, respectively, $P = \text{NS}$). In addition, PMN pretreatment with the compound MK886 (10 ng/ml), a specific inhibitor of leukotriene generation (31), did not alter baseline FMLP-driven PMN transmigration and did not effect the LXA_4 -elicited increase in PMN transepithelial migration (data not shown).

Staurosporine, a potent inhibitor of protein kinase C (PKC) (32), was assessed for its ability to inhibit the LXA_4 effect. Interestingly, staurosporine alone (10 nM final concentration) was found to inhibit PMN transepithelial migration ($93 \pm 5\%$ inhibition vs vehicle control, $n = 3$, $P < 0.001$). These data were also confirmed using the PKC inhibitor H7 (33) ($100 \mu\text{M}$ final concentration, $91 \pm 4\%$ inhibition compared to vehicle control, $n = 3$, $P < 0.001$). Likewise, the LXA_4 -elicited (10 nM) increment in transmigration was sensitive to staurosporine ($89 \pm 7\%$ inhibition compared to vehicle control, $n = 3$, $P < 0.001$). Preexposure of PMN to pertussis toxin (34) ($2 \mu\text{g/ml}$) also inhibited baseline FMLP-driven transmigration ($91 \pm 8\%$ inhibition compared to vehicle control, $n = 6$, $P < 0.001$). The LXA_4 -elicited (10 nM) increase in PMN transmigration ($46 \pm 3\%$ increase compared to control, $P < 0.01$) was also sensitive to PMN preexposure to pertussis toxin ($87 \pm 4\%$ inhibition of control, $n = 6$, $P < 0.001$).

We next assessed the possibility of differential sensitivity to staurosporine for baseline and LXA_4 -stimulated increases in FMLP-driven PMN transmigration. Staurosporine inhibited baseline PMN transepithelial migration in a dose-dependent manner ($94 \pm 4\%$, $96 \pm 9\%$, $67 \pm 11\%$, $54 \pm 8\%$, $35 \pm 11\%$, and $11 \pm 6\%$ inhibition compared to vehicle controls for concentrations of 100, 10, 1, 0.1, 0.01, and 0.001 nM staurosporine, respectively, $P < 0.01$ by ANOVA). From this dose response, we selected a concentration that was approximately half-maximal in inhibiting PMN transmigration (0.1 nM, see above). PMN were then preexposed to staurosporine (0.1 nM, 15 min, 37°C), washed free of inhibitor, and subsequently assessed for the LXA_4 effect on PMN transepithelial migration. Here, the LXA_4 -elicited increase in transepithelial migration of PMN was observed to be sensitive to PKC inhibition, since the relative inhibition by staurosporine was equivalent with and without LXA_4 ($54 \pm 6\%$ and $49 \pm 7\%$ decrease in total PMN transmigration for staurosporine-treated PMN in the presence and absence of LXA_4 , respectively, $P = \text{NS}$; both decreased compared to staurosporine-untreated controls, $n = 6$, $P < 0.025$). These

results indicate that LXA_4 -elicited increases in PMN transmigration in the apical-to-basolateral direction are not sensitive to inhibition of the cyclooxygenase pathway or the specific inhibition of leukotriene generation, but is sensitive to inhibitors of PKC.

Discussion

During inflammatory processes, PMN are recruited from the blood by signals derived at inflammatory sites. At sites of acute inflammation, PMN function may be regulated by a variety of inflammatory signals, including both protein- and lipid-derived signals. PMN function at organ-specific sites, including the intestine, is thought to contribute to epithelial dysfunction during disease. Here we report for the first time that the arachidonic acid-derived eicosanoid LXA_4 modulates PMN migration across a model human intestinal epithelium. In addition, we report that LXA_4 exerts an effect on transmigration in a polarized fashion.

LXA_4 enhances PMN transepithelial migration in the apical-to-basolateral direction. For technical reasons, previous studies of PMN transepithelial migration have focused on "nonphysiologically" oriented monolayers, in which leukocyte migration is in the apical-to-basolateral direction (11, 13, 14, 19, 35). PMNs preexposed to LXA_4 and driven to transmigrate across epithelial monolayers oriented nonphysiologically resulted in enhanced PMN migration (Figs. 1 and 2). The action of LXA_4 was found to be specific for PMN but not epithelial cells, since enhanced PMN migration in this direction was dose- and time-dependent, and no measurable effects on PMN transepithelial migration were observed when epithelial monolayers were preexposed to LXA_4 under conditions that promoted enhanced PMN migration. These results are consistent with previous studies which report that LXA_4 , in similar concentrations used here, was capable of activating PMN in vitro (36). In our model system, LXA_4 enhanced PMN transmigration in a manner independent to that of FMLP, since in all conditions PMN migration was driven toward a gradient of FMLP, suggesting that the proportion of PMN migration exceeding that of FMLP controls is dependent on a LXA_4 -mediated event. Moreover, these results suggest that the action of LXA_4 may be synergistic with FMLP, since LXA_4 by itself does not promote PMN migration in the absence of FMLP (see Results).

We have also found that preexposure of PMN to LXA_4 modulates migration of PMN in a polarized manner. That is, an opposite effect was observed depending on the direction of PMN migration. The observed effect of LXA_4 inhibition of PMN transmigration in the physiologically oriented (basolateral-to-apical) direction was dependent on concentration, as well as the duration of preexposure (Figs. 4 and 5). These effects were found to be selective for LXA_4 , since no effect was observed with the positional isomer LXB_4 (Fig. 6). As described for leukocyte movement across endothelia (38), PMN migration across epithelial monolayers is likely a multistep process requiring engagement and disengagement of several receptor-ligand complexes between PMN and epithelial cell. The specific events involved in PMN transepithelial migration are poorly understood at the present time, but in part requires the PMN $\beta 2$ integrin CD11b/CD18 and are independent of intercellular adhesion molecule-1 (14). In addition, PMN transepithelial migration can be regulated by exposure of T_{84} epithelial

monolayers to the lymphokine IFN- γ (19). In light of the polarized nature of this epithelium (17, 18, 37), it would not be surprising that the sequence by which PMN encounters epithelial ligands directly regulates PMN transmigration. Moreover, PMN migration across endothelia requires a sequential series of activation and deactivation steps on the PMN surface, of which lipid-derived activating factors may play an important role (reviewed in reference 38). Whether LXA₄ could act as a lipid-derived factor for expression of a crucial ligand in the regulation of PMN transmigration across epithelia is not known. Evidence to support this hypothesis is provided by a recent study characterizing lipoxin binding sites on human PMN (39). With a reported K_d of 0.5 nM and ~ 1,800 binding sites per cell, the range of LXA₄ concentrations used in the present study (0.01–10 nM) should provide maximal activation of subsequent signal transduction steps, most of which remain to be elucidated, but appears to involve a G protein-associated activation step (39) and possibly a signaling step through PKC as determined by inhibition using staurosporine (see Results).

Recent *in vivo* studies have shown that LXA₄ is an important inflammatory mediator at several distinct anatomic sites, including the lung (28), kidney (40), blood vessel (41), and hamster cheek pouch (26). The data reported here suggest that LXA₄-elicited alterations exert effects at the level of PMN and subsequently modulate PMN-epithelial interactions. Previous studies have shown that production of lipoxygenase products of arachidonic acid correlates with intestinal inflammation. Specifically, an enhanced conversion of arachidonate to 5-, 12- and 15-hydroxy-eicosatetraenoic acid (HETE) has been shown in ulcerative colitis homogenates (42) as well as increased biosynthesis of LTB₄ in Crohn's disease (43). The present results suggest that lipoxins, and specifically by their action on PMN, may play a role in intestinal disease.

Acknowledgments

The authors wish to thank Dr. John Gillard of Merck Frosst Centre for Therapeutic Research for the kind gift of the leukotriene biosynthesis inhibitor MK-886.

This work was supported by National Institutes of Health research grants DK35932 and DK33506 (J. L. Madara) and GM38765 (C. N. Serhan). Dr. Colgan is supported by an individual National Research Service Award postdoctoral fellowship (DK08777). Dr. Parkos is supported, in part, by a Career Development Award from the Crohn's and Colitis Foundation of America. Dr. Serhan is the recipient of the Clifford M. Clarke Science Award from the National Arthritis Foundation.

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