Arachidonic acid in postshock mesenteric lymph induces pulmonary synthesis of leukotriene B₄

Janeen R. Jordan,¹,² Ernest E. Moore,¹,² Eric L. Sarin,¹,² Sagar S. Damle,¹,² Sara B. Kashuk,¹ Christopher C. Silliman,¹,² and Anirban Banerjee¹

Departments of ¹Surgery, University of Colorado Denver; ²Denver Health Medical Center; and ³Bonfils Blood Center, Denver, Colorado

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Arachidonic acid in postshock mesenteric lymph induces pulmonary synthesis of leukotriene B₄. —Mesenteric lymph is the mechanistic link between splanchnic hypoperfusion and acute lung injury (ALI), but the culprit mediator(s) remains elusive. Previous work has shown that administration of a phospholipase A₂ (PLA₂) inhibitor attenuated postshock ALI and also identified a non-ionic lipid within the postshock mesenteric lymph (PSML) responsible for polymorphonuclear neutrophil (PMN) priming. Consequently, we hypothesized that gut-derived leukotriene B₄ (LTB₄) is a key mediator in the pathogenesis of ALI. Trauma/hemorrhagic shock (T/HS) was induced in male Sprague-Dawley rats and the mesenteric duct cannulated for lymph collection/diversion. PSML, arachidonic acid (AA), and a LTB₄ receptor antagonist were added to PMNs in vitro. LC/MS/MS was employed to identify bioactive lipids in PSML and the lungs. T/HS increased AA in PSML and increased LTB₄ and PMNs in the lung. Lymph diversion decreased lung LTB₄ by 75% and PMNs by 40%. PSML stimulated PMN priming (11.56 ± 0.29 nmol O₂⁻/min; 3.75 × 10⁵ cells/ml; P < 0.01) that was attenuated by LTB₄ receptor blockade (2.64 ± 0.58; P < 0.01). AA stimulated PMNs to produce LTB₄, and AA-induced PMN priming was attenuated by LTB₄ receptor antagonist. Collectively, these data indicate that splanchnic ischemia/reperfusion activates gut PLA₂-mediated release of AA into the lymph where it is delivered to the lungs, provoking LTB₄ production and subsequent PMN-mediated lung injury.

Integrative changes are needed to define the role of the mesenteric lymph and the non-ionic lipid fraction extracted from PSML primed PMNs for increased superoxide (O₂⁻) production, increased adhesion molecule surface expression, and also inhibited PMN apoptosis (9, 25).

Phospholipase A₂ (PLA₂), a proximal enzyme in the arachidonic acid (AA) cascade found in the gut, contributes in the generation of proinflammatory lipids via the lipoxygenase and cyclooxygenase pathways (22, 23). Increased activity of this enzyme has been established following gut I/R (24). Clinically, mortality related to multiple organ failure correlates with increased plasma levels of the secretory isoform of PLA₂ (27, 32, 33). Additionally, the administration of a PLA₂ inhibitor prevents lung injury related to splanchnic hypoperfusion following T/HS, and PLA₂ blockade abrogates PMN priming activity associated with the lipid fraction of PSML (16). AA is a biologically active lipid released from the cellular membrane by PLA₂ that can engage the leukotriene B₄ (LTB₄) receptor and initiate LTB₄ production with autocrine effects (11, 31). AA also promotes 5-lipoxygenase translocation to the nucleus, a key step in LTB₄ production (22, 31). LTB₄ is a non-ionic lipid recognized as a potent mediator of PMN chemotaxis and endothelial adherence as well as PMN priming and O₂⁻ production (22, 25). Additionally, LTB₄ has been invoked as a key proinflammatory mediator in an array of clinical disorders (3, 6). Our previous work in vitro has confirmed that LTB₄ induces robust priming of human PMNs (25). Animal studies in other laboratories have verified the important role of LTB₄ in the pathogenesis of acute lung injury (ALI) following splanchnic I/R (15, 18, 30). Consequently, we hypothesized that LTB₄ is the key mediator in PSML responsible for PMN-mediated ALI. However, mass spectrometric analysis of PSML failed to detect LTB₄ but rather indicated an increase in AA that can prime PMNs. We propose that gut PLA₂-dependent release of arachidonate into the mesenteric lymph provokes ALI via LTB₄ production.

METHODS

Animal experiments were performed under a protocol approved by the Institutional Animal Care and Use Committee at the University of Colorado Denver. All materials were purchased from Sigma Chemicals (St. Louis, MO) unless otherwise specified. Heparin was purchased from Elkins-Sinn (Cherry Hill, NJ) and Ficoll-Paque from Pharmacia Biotech (Uppsala, Sweden). AA was provided by Cayman Chemical (Ann Arbor, MI). The LTB₄ receptor antagonist CP-105,696

Address for reprint requests and other correspondence: E. E. Moore, Dept. of Surgery, Denver Health Medical Center, 777 Bannock St., Denver, CO 80204 (e-mail: ernest.moore@dhha.org).
Nitrogen and stored at plasma were mixed 1:1 with methanol. Samples were frozen in liquid to remove cellular components. An aliquot of lymph supernatant and lymph and blood samples were centrifuged at 5,000 rpm, and 1 ml of whole blood was taken at the initiation of shock. The intervals, and 1 ml of whole blood was taken at the completion of the third hour following resuscitation. The lungs were harvested and frozen in liquid nitrogen then stored at −80°C until processed. The right lung was infused with 3 ml of OCT (Fisher Scientific, Pittsburg, PA) mixed 1:1 with PBS. A section of the lower lobe was fast frozen and stored at −80°C until processed. Tissue sections (5 μm) were air-dried on slides and fixed with acetone:methanol (70:30, vol/vol) at −20°C for 10 min, then air-dried and blocked for 1 h at room temperature in 10% normal donkey serum in PBS. Rabbit anti-rat PMN IgG (Accurate Chemical, Westbury, NY) diluted 1:50 in PBS with 1% BSA was then added to the slide and incubated overnight at 4°C. Consecutive sections of the tissue were incubated with isotype to assess nonspecific binding. After slides were washed with PBS to remove excess antibody, 1:100 Alexa 488-conjugated donkey-antirabbit IgG (Molecular Probes, Eugene, OR) and 1:1,000 Alexa 633 Wheat Germ Agglutinin (Molecular Probes) in PBS with 1% BSA were incubated at room temperature for 1 h. After excess secondary antibody was washed, the sections were mounted and sealed. Images were taken on Zeiss Axiovert 100 with motorized stage control using the program Slidebook (III Intelligent Imaging Innovations, Denver, CO).

**Fig. 1.** Postshock mesenteric lymph (PSML) primes human polymorphonuclear neutrophils (PMNs). PSML increased PMN O2− production, compared with lymph collected before hemorrhagic shock, when stimulated by 1 μmol fMLP [maximal rate of O2− production (Vmax) of 11.56 ± 1.25 vs. 3.95 ± 0.29 nmol O2−/min; P < 0.01].

was provided by Pfizer (Groton, CT), and the antagonist LY-255283 was provided by Biomol (Plymouth Meeting, PA).

**T/Hs.** Adult male Sprague-Dawley rats weighing 350–375 g (Colorado State University) were housed in a climate-controlled barrier facility with 12-h light-dark cycles with free access to food and water. The animals were anesthetized using intraperitoneal pentobarbital (50 mg/kg), and the left femoral artery and vein were cannulated using 0.02-in. polyethylene tubing. A separate skin puncture was created to tunnel the catheters before closure of the groin incision. Using the arterial line, heart rate and blood pressure were continuously monitored with a Pro-Paq device (Protocol Systems, Beaverton, OR.). Following midline celiotomy, medial visceral rotation was performed to expose the mesenteric lymphatics. A 25-gauge needle affixed to silicized tubing was inserted into the cisterna chyli and exteriorized via a separate stab incision in the right flank. Mesenteric lymph was collected for 60 min before, during, and for 3 h after nonlethal hemorrhagic shock (mean arterial pressure 30 mmHg; 107 cells/ml) was stored at −80°C until processing. The right lung was infused with 3 ml of OCT (Fisher Scientific, Pittsburg, PA) mixed 1:1 with PBS. A section of the lower lobe was fast frozen and stored at −80°C until processed. Tissue sections (5 μm) were air-dried on slides and fixed with acetone:methanol (70:30, vol/vol) at −20°C for 10 min, then air-dried and blocked for 1 h at room temperature in 10% normal donkey serum in PBS. Rabbit anti-rat PMN IgG (Accurate Chemical, Westbury, NY) diluted 1:50 in PBS with 1% BSA was then added to the slide and incubated overnight at 4°C. Consecutive sections of the tissue were incubated with isotype to assess nonspecific binding. After slides were washed with PBS to remove excess antibody, 1:100 Alexa 488-conjugated donkey-antirabbit IgG (Molecular Probes, Eugene, OR) and 1:1,000 Alexa 633 Wheat Germ Agglutinin (Molecular Probes) in PBS with 1% BSA were incubated at room temperature for 1 h. After excess secondary antibody was washed, the sections were mounted and sealed. Images were taken on Zeiss Axiovert 100 with motorized stage control using the program Slidebook (III Intelligent Imaging Innovations, Denver, CO).

**Human PMN isolation.** Human PMNs isolated from heparinized blood obtained from healthy donors using dextran sedimentation, Ficoll gradient density centrifugation, and hypotonic lysis of contaminating red blood cells (35). The PMNs were resuspended in Kreb's Ringer phosphate with dextrose at pH 7.35 to a final concentration of 3.75 × 107 cells/ml. The final cell population was >99% PMNs by differential staining and was >99% viable by trypan blue exclusion.

PMN O2− anion generation by PMNs was measured by O2− dismutase-inhibitable cytochrome c reduction in 96-well microplates as described previously (35). The isolated PMNs were incubated with either buffer, preshock lymph, or postshock lymph alone or with the LTB4 receptor antagonist CP-105,696 (100 nM) for 5 min at 37°C. Isolated PMNs were also incubated with 3 μM AA alone or AA with 100 nM LY-255283 (LTB4 receptor antagonist) for 10 min. All priming assays were completed at 37°C in duplicate with a separate O2− dismutate blank and unstimulated control. In human PMNs, the respiratory burst was initiated with the addition of 1 μmol N-formyl-methionyl-leucyl-phenylalanine (fMLP) to experimental wells, and the maximal rate of O2− production (Vmax) was determined using the slope of the absorbance curve (35). Variability in PMN priming ability was standardized to priming with 2 μmol platelet activating factor (Paf), then stimulation with fMLP for each experiment (28). Agents were considered “priming” if comparable to the PMN-Paf response following addition of fMLP.

**Mass spectrometry.** A portion of each left lung was homogenized in HBSS, and protein content was determined using microbicinchoninic acid assay with a BSA standard. Samples containing 5 mg of protein were aliquoted, and ice-cold methanol was added to comprise 50% total volume. The samples were then centrifuged at 500 g for 10 min.
to precipitate proteins. The internal standards (2 ng each of [d₄]LTB₄ and [d₈]5-HETE) were added to the supernatants, samples were diluted with water to a final concentration of methanol of <15%, then lipid extraction was performed using a solid-phase extraction cartridge [Oasis HLB 1cc (30 mg), Waters], which was preactivated with 1 ml of MeOH and then 1 ml of H₂O. The metabolites were eluted from the cartridge with 1 ml of methanol, then dried and reconstituted in 40 μl of HPLC solvent A (8.3 mM acetic acid buffered to pH 5.7 with NH₄OH) + 20μl solvent B (AcCN/MeOH; 65/35; vol/vol). Aliquots (25 μl) of plasma, lymph, and lung samples were injected into a HPLC system, and separation of metabolites was conducted using a C18 column (Gemini 150 × 2 mm, 5 μm, Phenomenex) eluted at a flow rate of 200 μl/min with a linear gradient from 45 to 98% of mobile phase B. Solvent B was increased from 45 to 75% in 13 min, to 98% in 2 min, and held at 98% for another 11 min. The HPLC system was directly interfaced into the electrospray source of a triple quadrupole mass spectrometer where analyses were performed in the negative ion mode using multiple reaction monitoring of the specific transitions: m/z 335 → 195 for LTB₄, m/z 339 → 197 for [d₄]LTB₄, m/z 303 → 205 for AA, and m/z 327 → 116 for [d₈]5-HETE. Quantitations were determined using a standard isotope dilution curve ([d₄]-LTB₄ for LTB₄ and [d₈]5-HETE for AA) (13). An additional experiment was performed employing 1 × 10⁷ quiescent human PMNs, which were incubated with 3 μM AA for 10 min then stimulated with 1 μM fMLP. Ice-cold methanol was added to comprise 50% of the total volume; then the samples were then stored at −80°C until processed by reverse-phase high-pressure liquid chromatography with triple quadrupole mass spectrometry (LC/MS/MS) for LTB₄ production.

**Statistical analysis.** All data are represented as means ± SE. Statistical differences were determined among groups by paired or unpaired Student’s t-test. A p-value of 0.05 or less was considered significant. The results are expressed as mean ± SE.

**Fig. 3.** PMN infiltration into the lung parenchyma following hemorrhagic shock. A: lung tissue following trauma/hemorrhagic shock (T/HS) without lymphatic diversion. PMNs are colored green, and the cellular membranes appear in blue. There is loss of the alveolar architecture with diffuse PMN infiltration. B: lung tissue following T/HS with lymphatic diversion. The overall architecture is maintained, and there are fewer PMNs, indicating that diversion of the mesenteric lymph duct decreases PMN infiltration and lung injury.

**Fig. 4.** LTB₄ production in the lung. LTB₄ levels by LC/MS/MS were increased nearly eightfold in the lungs following T/HS in undiverted animals compared with control (104.5 ± 18.7 vs. 13.4 ± 4.7 pmol; P < 0.01). Diversion of the lymph by cannulation during shock reduced the amount of LTB₄ produced in the lung to 27.5 ± 17.0 pmol (P < 0.05). Therefore, diversion of the mesenteric lymph before hemorrhagic shock decreased LTB₄ production in the lung.

**Fig. 5.** Mass spectrometry of PSML. Preshock and postshock lymph were evaluated by LC/MS/MS. Spectra below demonstrate the absence of LTB₄ in either the preshock or postshock lymph (red trace). The blue traces represent the internal standards added to each sample (P < 0.01).
independent (when appropriate) ANOVA followed by a Bonferroni post hoc analysis. Significance is reported as \( P < 0.05 \).

**RESULTS**

**PMN priming by PSML is LTB4 dependent.** PSML increased PMN \( \text{O}_2^- \) production when stimulated by \( 1 \mu\text{mol fMLP} \) with a \( V_{\text{max}} \) of \( 11.56 \pm 1.25 \) vs. \( 3.95 \pm 0.29 \) nmol \( \text{O}_2^-/\text{min} \) (with \( 3.75 \times 10^7 \) cells/ml) (Fig. 1; \( n = 5; \ P < 0.01 \)). PSML added to PMNs pretreated with a LTB4 receptor antagonist (CP-105,696, 100nM) had attenuated priming \( 2.64 \pm 0.58 \) vs. \( 11.56 \pm 1.25 \) nmol \( \text{O}_2^-/\text{min} \) (Fig. 2; \( n = 5; \ P < 0.01 \)). Furthermore, PMN accumulation in the lung was decreased by 40% with lymph diversion during hemorrhagic shock (Fig. 3; \( n = 3 \)). The PMNs are displayed in green (Alexa 488), and the cellular membranes are displayed in blue (Alexa 633 Wheat Germ Agglutinin). These data indicate that PSML bioactivity is attenuated by LTB4 receptor blockade, and diversion of the PSML decreases PMN infiltration and subsequent lung injury.

LTB4 is present in the lung following T/HS but not lymph. LTB4 was evaluated by LC/MS/MS in both lung or preshock and postshock lymph. LTB4 levels were increased nearly eightfold in the lungs following T/HS compared with control (\( 104.5 \pm 18.7 \) vs. \( 13.4 \pm 4.7 \) pmol; \( n = 4; \ P < 0.01 \)). Diversion of the lymph by cannulation during shock reduced the amount of LTB4 produced in the lung to \( 27.5 \pm 17.0 \) pmol (Fig. 4; \( n = 4; \ P < 0.05 \)). Surprisingly, LTB4 was not detected in the lymph (Fig. 5; traces represent labeled isotope control in blue and lymph in red; \( n = 3; \ P < 0.01 \)). These data suggests that, although LTB4 is not present in the lymph, PSML contains a mediator capable of increasing LTB4 in the lung.

**Fig. 6.** Arachidonic acid (AA) is increased in PSML. LC/MS/MS analysis revealed that AA, the precursor for leukotrienes, was found to increase modestly in PSML (\( P < 0.05 \)). Red trace demonstrates AA found in the lymph compared with [d8]-HETE, the added internal standard, which is displayed as the blue trace (\( P < 0.05 \)).

**Fig. 7.** Delivery of AA to the systemic circulation by PSML. Although the actual concentrations in the PSML were moderately elevated compared with preshock values, we have previously shown that lymph flow following shock and resuscitation consistently increases over threefold in the first hour of resuscitation alone (9). Therefore, the minimum amount of AA in PSML delivered to the lungs increased from \(-129.5\) to \(749.8 \text{ ng/h postshock} (P = 0.08)\).

**Fig. 8.** LTB4 production by AA-stimulated PMNs. In vitro, 3 \( \mu\text{M AA} \) induced a ninefold increase in LTB4 production in PMNs (\( 1 \times 10^7 \) cells/ml) when stimulated with \( 1 \mu\text{mol fMLP} \) compared with control (\( P < 0.05 \)).

**Fig. 9.** AA primes PMNs that is attenuated with LTB4 receptor inhibition. AA (3 \( \mu\text{M} \)) primed PMNs (\( 3.75 \times 10^7 \) cells/ml) for increased \( \text{O}_2^- \) release when stimulated by \( 1 \mu\text{mol fMLP} \) (\( V_{\text{max}} \) of \( 5.74 \pm 2.2 \) vs. \( 1.33 \pm 0.22 \) nmol \( \text{O}_2^-/\text{min} \)). The addition of 100 nM LTB4 receptor antagonist (LY-255283) abrogated the AA-stimulated PMN priming to \( 2.67 \pm 1.5 \) nmol \( \text{O}_2^-/\text{min} (P < 0.05) \).
AA is increased in PSML and stimulates PMN LTB4 production. LC/MS/MS analysis revealed that AA, the precursor for leukotrienes, was found to increase in PSML (Fig. 6; lymph in red and internal standard in blue; n = 3; P < 0.05). The concentrations in the PSML were elevated compared with preshock values. However, considering that lymph flow consistently increases greater than threefold following shock and resuscitation (9), then the minimum the amount of AA in PSML delivered to the lungs increased from ~129.5 to 749.8 ng/h postshock (Fig. 7; n = 3; P = 0.08). Moreover, the AA concentration in the plasma following T/HS increased by 38% in undiverted animals compared with 12% in diverted animals. In vitro, 3 μM AA induced a ninefold increase in LTB4 production in quiescent PMNs (1 × 10^7 cells/ml) compared with control (Fig. 8; P < 0.05) and primed PMNs (3.75 × 10^7 cells/ml) for increased O2 burst when stimulated by 1 μmol fMLP (V_{max} of 5.74 ± 2.2 vs. 1.33 ± 0.22 nmol O2/min). The addition of 100 nM LTB4 receptor antagonist (LY-255283; Biomol, Plymouth Meeting, PA) abrogated the AA-stimulated PMN priming to 2.67 ± 1.5 nmol O2/min (Fig. 9, n = 3; P < 0.05). AA has been shown to act as a ligand for the LTB4 receptor, which, once activated, stimulates leukotriene production (31). These data indicate that AA is increased in the PSML and is capable of PMN priming and inducing LTB4 production by PMNs.

DISCUSSION

Splanchnic hypoperfusion plays a critical role in the pathogenesis of multiple organ failure (17, 20). Initial rodent models invoked gut bacterial translocation as the unifying pathophysiological concept (5, 29). However, the inability to confirm translocation from the gut in the setting of major torso trauma (21) coupled with contradictory results from subsequent hemorrhagic shock models (14, 17) challenged the veracity of this theory. Recent work demonstrating that ALI following T/HS can be eliminated by diversion of the mesenteric lymphatics has redirected the investigative focus (4, 19). Subsequently, PSML has been demonstrated to prime PMNs for the release of O2 (35), and this priming ability was contained in the lipid fraction of the lymph (10). Furthermore, this PSML lipid fraction delays PMN apoptosis, thereby enhancing cytotoxic potential, and this effect is neither endotoxin nor cytokine dependent (9, 10, 17).

PLA2 is a large group of enzymes responsible for hydrolyzing cell membrane phospholipids producing lysophospholipids and free fatty acids (22). Of the two main types, secretory and intracellular, secretory PLA2 (sPLA2) represents the major culprit in inflammation and, as such, is considered a key target for pharmacological intervention (34). Of particular interest among the liberated free fatty acids is AA and its multiple products, the eicosanoids. These molecules are synthesized de novo following PLA2 activity and include leukotrienes, prostaglandins, thromboxanes, and lipoxins. The leukotrienes represent major mediators of inflammation, with LTB4 recognized as a remarkably potent effector of PMN chemotaxis and aggregation as well as enhanced adhesion to the endothelium (8, 22). Targeted disruption of LTB4 synthesis or activity confers a distinct survival advantage in response to PLA2-derived lipids (1, 12). Additionally, LTB4 is a consistent mediator of ALI in animal models (7), and pretreatment with the PLA2 inhibitor quinacrine attenuates lung injury in a rodent model of splanchnic I/R (10). The effect of this inhibition alters the PSML lipid profile as observed by normal-phase HPLC (10), implying that regulation of the lipid component(s) within PSML may be an important means of mediating gut-derived cytotoxicity following T/HS. An extension of this work, the present study sought to identify a specific lipid and its relationship to PSML-associated cytotoxicity. Therefore, we inhibited the PMN receptor in vitro to block the effects of LTB4 presumably carried in the PSML.

However, our inability to identify LTB4 in the PSML by mass spectrometry was unexpected. Instead, the PSML contained high concentrations of AA, a LTB4 precursor. Interestingly, AA has been shown to activate the LTB4 receptor or independently initiate LTB4 production with further autocrine effects, including priming of the fMLP-activated respiratory burst (25, 31). AA has also been noted to participate in the initiation of 5-lipoxygenase translocation, a key step in LTB4 production (22, 30). Therefore, we now believe that it is the release of AA into the PSML by the action of PLA2 that ultimately results in distant organ injury such as ALI following T/HS. In the distal tissues, AA may stimulate the production of inflammatory mediators, but it is possible that AA is also processed to metabolites such as LTB4 via transcellular metabolism that promotes PMN and granulocyte chemotaxis and activation. Previous work has shown that ischemic organs have the ability to produce AA that is delivered to PMNs for processing and transcellular metabolism (2, 26). The present study supports this hypothesis and, in fact, represents a new and unique circumstance whereby a substance produced by an ischemic organ is transported and processed in another distant organ to produce inflammation.

In conclusion, we propose that splanchnic I/R activates gut PLA2 to release AA into PSML where it is conveyed to the lungs, presumably bound to carrier proteins. AA may then initiate inflammation and attract additional PMNs to infiltrate locally. These stimulated PMNs produce LTB4 but also produce and release LTA4, which is substrate for the lung endothelium and epithelium via transcellular metabolism to amplify further LTB4 production and, therefore, incite subsequent lung injury.

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REFERENCES

4. Deich EA, Adams C, Lu Q, Xu DZ. A time course study of the protective effect of mesenteric lymph duct ligation on hemorrhagic shock-


