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Inhibition of Inducible Nitric Oxide Synthase Prevents LPS-Induced Acute Lung Injury in Dogs

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Nitric oxide (NO) is produced by inducible NO synthase (iNOS) after LPS stimulation, and reacts with superoxide to form peroxynitrite. We hypothesize that in LPS-induced lung injury, NO generated by iNOS plays a key role through the formation of peroxynitrite. We developed an acute lung injury dog model by injecting LPS, and examined the effects of selective iNOS inhibitors, aminoguanidine (AG) and S-methylisothiourea sulfate (SMT), on the LPS-induced lung injury. At 24 h after LPS injection, arterial oxygen tension and mean arterial pressure decreased, and shunt ratio and lung wet-to-dry weight ratio increased. On histology, the LPS group had marked neutrophil infiltration and widening of the alveolar septa. On immunohistochemistry, iNOS and nitrotyrosine, a major product of nitration of protein by peroxynitrite, were observed in the interstitium, capillary wall, and neutrophils in the airspaces of the LPS group. Treatments with AG and SMT prevented worsening of gas exchange, hemodynamics, and wet-to-dry weight ratio. On histology, AG and SMT treatments markedly suppressed lung injury, iNOS protein, and nitrotyrosine production. We conclude that NO released by iNOS may play a critical role in the pathogenesis of LPS-induced acute lung injury. This study suggests that iNOS inhibitors may have potential in the treatment of LPS-induced acute respiratory distress syndrome. The Journal of Immunology, 1998, 160: 3031–3037.

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1 Abbreviations used in this paper: ARDS, acute respiratory distress syndrome; A-aDO2, alveolar-arterial oxygen difference; AG, aminoguanidine; cNOS, constitutive nitric oxide synthase; EVLW, extravascular lung water; FRC, functional residual capacity; iNOS, inducible nitric oxide synthase; L-NMMA, Nω-nitro-L-arginine; MAP, mean arterial pressure; MPAP, mean pulmonary arterial pressure; NO, nitric oxide; NOS, nitric oxide synthase; PAF, platelet-activating factor; PaO2, partial pressure of oxygen; PCWP, pulmonary capillary wedge pressure; P-V, pressure-volume; Q˙/Q˙, intrapulmonary shunt ratio; SMT, S-methylisothiourea sulfate; TLC, total lung capacity; W/D, wet-to-dry weight.
24 h on a surgical table using a heating pad and were administered Ringer’s solution throughout the experiments (4 mL/kg/h). Pressures and ventilation were recorded on a six-channel strip-chart recorder (Rectigraph 8K; San-ei NEC, Tokyo, Japan).

**Study protocol**

Experimental groups were as follows: 1) control group (n = 7), animals were injected with 20 ml of saline; 2) LPS group (n = 7), animals were injected with LPS i.v.; 3) AG group (n = 5), AG was administered i.v. throughout the experiment; 4) LPS + AG group (n = 7), AG administration was started before LPS injection; 5) SMT group (n = 5), SMT was injected continuously throughout the experiment; and 6) LPS + SMT group (n = 5), SMT administration was started before LPS injection. LPS (Escherichia coli serotype 0111; B4; Sigma Chemical Co., St. Louis, MO), 20 mg/kg, was dissolved in 20 ml of saline and injected i.v.: in 10 min. Intravenous administration of AG or SMT (Sigma Chemical Co.) was started 30 min before the injection of saline or LPS at a rate of 2 mg/kg or 1 mg/kg/h throughout the experiment, respectively.

Hemodynamic parameters, pulmonary gas exchange, and pulmonary function were measured at 0, 3, 6, 12, and 24 h after LPS or saline injection. At the end of the experiments, the animals were killed by injection of potassium chloride, and the lungs were excised immediately for measurement of wet-to-dry weight (W/D) ratio and for histologic examination.

**Hemodynamics**

Mean arterial pressure (MAP) was measured by a catheter placed in the femoral artery connected to a pressure transducer (model 023XL; Spectramed, Stratham, CA). Both mean pulmonary arterial pressure (MPAP) and pulmonary capillary wedge pressure (PCWP) were measured with a Swan-Ganz catheter connected to pressure transducers (model 023XL; Spectramed).

**Pulmonary gas exchange**

Partial pressures of oxygen (PaO₂) and carbon dioxide, and pH of arterial blood were measured with a blood gas analyzer (BGM IL-1312; Instrumentation Laboratory, Milan, Italy). Hemoglobin concentration, and the oxygen saturation of arterial blood (SaO₂) and mixed venous blood (SO₂) were measured with a CO-Oximeter (IL-482; Instrumentation Laboratory). Mixed venous samples were collected through a Swan-Ganz catheter. Alveolar-arterial oxygen difference (A-aDO₂) and intrapulmonary shunt ratio (Qs/Qt) were calculated using standard formulae.

**Pressure-volume curve**

The pressure-volume (P-V) curve of the lung was measured by a previously described method (24). Transpulmonary pressure was monitored as a pressure difference between airway pressure and esophageal pressure with a differential pressure transducer (MP-45; Validyne, Northridge, CA). Total lung capacity (TLC) and functional residual capacity (FRC) were determined as the absolute air volume at a transpulmonary pressure of 30 and 5 cm H₂O, respectively. Absolute lung volume at FRC was measured by a gas dilution method using neon gas. Before the measurement of the P-V curve, the animal was mechanically hyperventilated using a respirator (SN-3032 INDUCIBLE NITRIC OXIDE SYNTHASE IN ACUTE LUNG INJURY)

**Gas exchange**

Intravascular lung water (EVLW) was measured using a modification of a previously described technique (24, 25). Briefly, after all measurements were finished 24 h after LPS or saline injection, three blocks (1 × 1 × 1 cm) were cut from the upper, middle, and lower lobes and homogenized. Each lung homogenate was dried in a 50°C oven until weights were unchanged on 2 consecutive days (7 to 10 days), and dry weight was measured. Other homogenate was centrifuged and hemoglobin was measured in a spectrophotometer (U-1100; Hitachi, Tokyo, Japan) on the cleared supernatant and the whole blood. Then the weight of the blood in the lungs was calculated and EVLW was obtained as a difference between lung water and blood water. The bloodfree W/D ratio was the ratio of EVLW plus the dry weight to the dry weight. An average value of three sites of the lungs was reported.

**Lung histology**

The left lower lobe was excised and inflated with 10% formaldehyde solution at a pressure of 25 cm H₂O for 24 h. After fixation, the lung tissue was sectioned sagittally every 2 to 5 mm, and 10 blocks were sampled randomly for evaluation of histology. These sections were embedded in paraffin and cut to a thickness of 5 µm. They were then stained with hematoxylin-eosin (H-E).

**Immunofluorescent staining for iNOS and nitrotyrosine**

Paraffin-embedded lung tissue was stained with immunofluorescence. The staining was performed as previously described, with minor modifications (20, 26). The sections were dewaxed, dehydrated, and incubated with 10% normal goat serum to block nonspecific protein adsorption. Then the sections were incubated with polyclonal anti-mouse iNOS Ab (diluted 1:500; Affinity Bioreagents, Golden, CO) or anti-nitrotyrosine polyclonal Ab (diluted 1:100; Upstate Biotechnology, Lake Placid, NY) at 4°C overnight. The labeled Ags were visualized after incubation with FITC-conjugated goat anti-rabbit Ig (diluted 1:10; Kirkegaard and Perry, Gaithersburg, MD) at 4°C overnight. Cross-reactivity of anti-mouse iNOS Ab to canine iNOS was confirmed by Western blotting (data not shown). The tissue was then washed with ice-cold PBS to remove unbound Ab, overlaid with a drop of glycerol/PBS (9:1) mounting medium containing 0.01% phenylenediamine to prevent fluorescence breaching, and covered with a coverslip. In addition, we tested the staining with nonspecific IgG. Lung sections were observed with a fluorescence microscope (model BH2-RFC; Olympus, Tokyo, Japan).

**Neutrophil chemotaxis**

Neutrophils were isolated from peripheral blood of four dogs that were not used for in vivo studies (27). Neutrophil chemotaxis activity was determined by the leading front method using a 48-well microchemotaxis chamber (Neuroprobe, Cabin John, MD), as described elsewhere (27, 28). To examine the effects of iNOS inhibitors on neutrophil chemotaxis, neutrophils (4 × 10⁶ cells/ml) were preincubated with AG (10⁻³ M), SMT (10⁻³ M), or vehicle for 30 min at 37°C. Neutrophils were then placed in the upper compartment of the chamber and were allowed to migrate through a nitrocellulose filter of 3.0 µm pore size (Neupore) toward human IL-8 (10⁻³ M) or PAF (10⁻⁶ M) in the well of the lower compartment for 24 min at 37°C. Human IL-8 has been reported as chemotactic for dog neutrophils (28). The concentrations of IL-8 and PAF were chosen because they caused maximal chemotaxis in our preliminary dose-response studies and in previous studies (28). Chemotactic response was expressed as distance of migration (µm).

**Statistical analysis**

All results are expressed as mean ± SE. Statistical differences among group means were determined with one-way or two-way ANOVA with repeated measures, followed by a post hoc comparison using Newman-Keuls test. A p value of <0.05 was considered significant. The STATISTICA statistical software package (StatSoft, Tulsa, OK) was used.

**Results**

All animals survived for 24 h after LPS injection.

Gas exchange

In the LPS group, PaO₂ decreased gradually during the experiment (p < 0.01 by ANOVA) (Fig. 1). At 24 h after LPS injection, PaO₂ decreased from 103.6 ± 2.6 mm Hg to 67.4 ± 6.1 mm Hg (p < 0.01). Treatments with AG and SMT prevented the decrease in PaO₂ in LPS-injected animals, and no changes in PaO₂ were observed in the control, AG, and SMT groups. A-ADÒ₂ widened significantly at 12 and 24 h in the LPS group (from 5.3 ± 3.4 mm Hg at baseline to 21.7 ± 7.1 at 12 h and to 39.5 ± 8.6 mm Hg at 24 h, p < 0.05 and p < 0.01, respectively). However, treatments with AG and SMT prevented the increase in A-ADÒ₂ by LPS. No change in A-ADÒ₂ was observed in the control, AG, and SMT groups. In the LPS group, Qs/Qt increased gradually from 12 ± 3% at baseline to 48 ± 8% at the end of the experiment (p < 0.01) (Fig. 1). In contrast, treatments with AG and SMT prevented the increase of Qs/Qt. No changes in these parameters were observed in the control, AG, and SMT groups.
Hemodynamics

In the LPS group, the MAP started to decrease 3 h after LPS injection and recovered at 6 h, but finally declined by 15% at 24 h (p < 0.01 by ANOVA), although the control group showed no change in MAP throughout the experiment (Fig. 2). Treatments with AG and SMT prevented the decrease in MAP in LPS-injected animals. The MPAP and PCWP remained unchanged throughout the experiment in all groups.

P-V curve

In the LPS group, the P-V curve shifted downward 12 and 24 h after LPS injection (p < 0.01 by ANOVA, Fig. 3), and TLC decreased to 86.1 ± 4.4% of baseline values at 12 h and to 80.1 ± 4.7% at 24 h (p < 0.01). AG and SMT prevented the downward shift of the P-V curve by LPS. Neither the control, nor AG, nor SMT group caused changes in the P-V curve.

W/D ratio of the lung

The W/D ratio, a parameter of pulmonary edema, was increased in the LPS group (p < 0.01 by ANOVA) (Fig. 4). Treatments with AG and SMT prevented the increase in the W/D ratio (p < 0.05 and p < 0.01, respectively). Neither the control, nor AG, nor SMT group showed an increase in the W/D ratio.

Histology

At 24 h after LPS injection, there was a marked inflammatory cell infiltration in the interstitium and airspaces of the lung, predominantly composed of neutrophils (Fig. 5B). Interstitial edema and vascular congestion were also observed. Treatments with AG and SMT markedly attenuated the neutrophil infiltration and lung injury (Fig. 5, D and F). No inflammatory change was observed in the control, AG, and SMT groups (Fig. 5, A, C, and E).

FIGURE 1. Serial changes in PaO₂ (A), A-aDO₂ (B), and Q̇O₂/Q̇T (C) of the six groups: control (open circles); LPS (closed circles); AG (open triangles); LPS + AG (closed triangles); SMT (open squares); and LPS + SMT (closed squares). LPS injection decreased PaO₂ (A), and increased A-aDO₂ (B) and Q̇O₂/Q̇T (all, p < 0.01 by ANOVA). *p < 0.05, †p < 0.01 compared with the baseline value in the LPS group. ‡p < 0.01 compared with the other five groups 24 h after LPS injection. §p < 0.05 compared with the control, AG, SMT, and LPS + SMT groups 12 h after LPS injection.

FIGURE 2. Serial changes in MAP (A), PCWP (B), and MPAP (C). In the LPS group, MAP decreased (p < 0.01 by ANOVA), but MPAP did not change. *p < 0.05, †p < 0.01 compared with the baseline value in the LPS group. ‡p < 0.01 compared with the other five groups 24 h after LPS injection.

FIGURE 3. P-V curves at baseline (open circles), 12 h (closed circles, upper panel) and 24 h (closed circles, lower panel) after LPS injection. In the LPS group (B), the P-V curve shifted downward 12 and 24 h after LPS injection (both, p < 0.01 by ANOVA). In the control group (A), LPS + AG group (C), LPS + SMT group (D), AG group (not shown), and SMT group (not shown), the P-V curves showed no change. SEs of each group are similar and are shown only in B. Arrows represent the direction of volume change. *p < 0.05, †p < 0.01 compared with the baseline at each transpulmonary pressure.
iNOS immunoreactivity in the lung

Paraffin-embedded sections from the LPS group exhibited significant immunostaining with the polyclonal Ab to iNOS (Fig. 6). In the alveolar walls and capillaries of the LPS group, immunostaining of iNOS was demonstrated (Fig. 6B). Patchy staining of neutrophils and alveolar macrophages was also observed. In both the LPS + AG group and LPS + SMT groups, however, immunostaining of iNOS was markedly attenuated, and only weak staining of the alveolar walls was observed (Figs. 6D). No significant staining was detected in the control, AG, and SMT groups (Fig. 6, A, C, E, and F). Minimal background staining was observed in all six groups stained with nonspecific IgG (Fig. 6G).

Immunoreactivity of nitrotyrosine

Fluorescent images of the lung specimens labeled with polyclonal Ab to nitrotyrosine are shown in Figure 7. In the lung specimens of the LPS group, immunohistochemical staining of protein nitrotyrosine residues was observed throughout the lung (Fig. 7B). The lung interstitium, alveolar epithelium, alveolar exudates, and capillary wall were strongly stained. Alveolar macrophage and intraalveolar neutrophils exhibited significantly strong staining. With treatments of AG and SMT, the alveolar septa and alveolar macrophages were only weakly stained (Fig. 7, D and F). Scant staining of the alveolar septa was observed in the lung tissues of the control, AG, and SMT groups (Fig. 7, A, C, and E). Minimal background staining was observed in all six groups that were stained with nonspecific IgG (Fig. 7G).

Neutrophil chemotaxis

Neutrophils showed chemotaxis to IL-8 and PAF (Table I). Pretreatment with either iNOS inhibitor did not affect random migration (data not shown). AG did not affect neutrophil chemotaxis in response to either IL-8 or PAF. SMT slightly attenuated neutrophil chemotaxis in response to IL-8, but it was not statistically significant.

Discussion

We have shown that LPS injection in dogs causes severe hypoxemia and increases shunt ratio. On histology, interstitial edema and marked neutrophil infiltration in the lung were observed. Intense immunofluorescent staining of iNOS and nitrotyrosine, a specific marker for the presence of peroxynitrite, was observed in capillary wall and alveolar wall. Treatments with AG and SMT almost completely attenuated these physio-

logic and histologic changes and the production of peroxynitrite. The localization of iNOS and peroxynitrite suggests that NO may be generated by the induction of iNOS, and peroxynitrite may be responsible in part for the microvascular damage in acute lung injury induced by LPS.

In sepsis, toxic products activate systemic host defenses including neutrophils, macrophages, monocytes, endothelial cells, and the complement system (3). The activated cells produce toxic host mediators such as cytokines, kinins, eicosanoids, NO, and superoxides (2, 3, 29). Neutrophils have been implicated specifically in the pathogenesis of most cases of human sepsis (1, 30, 31). Consistent with these reports, our model demonstrates that neutrophils accumulated markedly in the interstitium and airspaces of the lung. In our study, treatment with iNOS inhibitors attenuated neutrophil sequestration in the lung. In several animal models of inflammation, a selective inhibitor of iNOS, N-iminoethyl-L-lysine, suppressed the infiltration of inflammatory cells (32, 33). However, the mechanisms by which iNOS inhibitors attenuate infiltration of inflammatory cells are unclear. N°-monomethyl-L-arginine (L-NMMA), an inhibitor of both isoforms of NOS, inhibits chemotaxis in neutrophils (34). It is also reported that nonspecific NOS inhibitors...
attenuated chemotaxis of peripheral blood monocyte, but an iNOS inhibitor did not (35). In the present study, both AG and SMT did not affect neutrophil chemotaxis, suggesting that iNOS inhibitors have no direct action on unstimulated neutrophil chemotaxis. Exogenous NO elicits chemotaxis of neutrophils (36). Therefore, attenuation of neutrophil infiltration by iNOS inhibitors may be caused by inhibition of NO production. Thus, treatment with NOS inhibitors attenuates neutrophil accumulation into the lung in LPS-injected animals.

Large amounts of NO produced by iNOS induction interact with oxygen free radicals derived from neutrophils and macrophages to form peroxynitrite at diffusion-limited reaction (11, 12). Peroxynitrite causes extensive tyrosine nitration and, as a result, forms nitrotyrosine (29). Thus, peroxynitrite is a potent and versatile oxidant that can attack many types of biologic molecules and has strong oxidizing and cytotoxic properties (29, 37). Excess production of NO is reported to contribute to the lung injury induced by immune complexes (13) or paraquat (38), and peroxynitrite is reported to be an important tissue-damaging product (13, 38). Recently, it has been reported that, in lung ischemia-reperfusion, nitrotyrosine is increased, and peroxynitrite is thought to be a causative factor of oxidative lung injury (39).

**FIGURE 6.** Immunofluorescence image of lung specimens labeled with anti-iNOS Ab. A, Control group: no immunostaining of iNOS. B, LPS group: marked immunostaining of iNOS in alveolar walls, capillaries, neutrophils, and alveolar macrophages. C, AG group: no significant staining is detected. D, LPS + AG group: weak staining of the alveolar walls is observed. E, SMT group: no staining is observed. F, LPS + SMT group: no staining is observed. G, Nonspecific IgG staining of LPS group: minimal background staining is observed. Original magnification: ×66.

**FIGURE 7.** Immunofluorescent image of lung specimens labeled with Ab to nitrotyrosine. A, Control group: no immunostaining of nitrotyrosine. B, LPS group: marked immunofluorescence is observed in the interstitium, alveolar epithelium, alveolar exudate, and capillary wall. In addition, alveolar macrophages and intra-alveolar neutrophils show strong staining. C, AG group: scant staining of the alveolar septa is observed. D, LPS + AG group: only weak staining in the alveolar septa and alveolar macrophages is observed. E, SMT group: scant staining is observed. F, LPS + SMT group: weak staining is observed. G, Nonspecific IgG staining of LPS group: minimal background staining is observed. Original magnification: ×66.
Several studies have shown that nitrotyrosine levels in the lung increased in patients with ARDS and in lung injury models (19, 20, 40), although these studies did not provide direct evidence that peroxynitrite contributed to lung injury. In our study, iNOS inhibitor treatment in LPS-injected animals prevented the development of pulmonary edema. In immunohistochemistry studies of the LPS group, staining of iNOS was markedly increased, and immunofluorescent staining of nitrotyrosine residue was strongly observed in the interstitium, alveolar epithelium, alveolar exudate, and capillary wall. This localization of iNOS and nitrotyrosine indicates that LPS causes the induction of iNOS and produces excess amounts of NO, resulting in the formation of peroxynitrite in the vascular endothelium and/or blood-borne elements. Thus, iNOS inhibitors prevent the generation of peroxynitrite and the development of pulmonary edema. It has been suggested previously that peroxynitrite may be involved in vascular injury in the acute inflammatory response (13, 38). In our study, therefore, peroxynitrite may have injured the endothelium of the microvasculature, causing increased permeability and edema.

The inducible isofrom of NOS is responsible for the excess production of NO in sepsis of animals, leading to the development of shock (16, 17, 41). In our study, MPAP did not change, although MAP was slightly decreased by LPS. This may indicate that lung injury of our dog model was mild. AG and SMT prevented the decrease in MAP by LPS. Both AG and SMT are selective inhibitors of iNOS and much less effective inhibitors of cNOS (21, 22). L-NMMA, a nonselective inhibitor of NOS, inhibits endothelin-induced hypotension (16, 17). In addition, L-α-amino-γ-arginine, an inhibitor of iNOS, blocks the decrease in MAP by endotxin (42). These findings suggest that NO generated from iNOS may cause LPS-induced hypotension.

Immunostaining of iNOS was observed in the alveolar wall, pulmonary capillaries, macrophages, and neutrophils in our model. This indicates that LPS injection stimulates not only endothelium but also neutrophils and macrophages to induce the production of iNOS. AG and SMT attenuated immunostaining of both iNOS and peroxynitrite. Although both AG and SMT are selective inhibitors of iNOS enzyme activity and suppress NO production (21), the level of iNOS protein was found to decrease in our study. In an adjuvant-induced arthritis model, a selective inhibitor of iNOS (N-iminoethyl-L-lysine) suppressed the production of NO and immunostaining of iNOS (33). This effect on iNOS immunostaining is similar to ours. Recently, Ruetten and Thiemermann have shown that both AG and aminoethyl-isothioura, selective iNOS inhibitors, inhibit not only iNOS activity but also the expression of iNOS protein in the rat lung and macrophages challenged with LPS, although nonselective inhibitors of NOS such as L-NMMA and L-α-nitro-γ-arginine methyl ester do not inhibit the expression of iNOS (43). These may suggest that some inhibitors of iNOS have other effects (on signal transduction) that prevent the expression of iNOS. Although the exact mechanism is unclear, iNOS inhibitors can suppress the induction of iNOS itself, in addition to inhibition of iNOS enzyme activity.

The P-V curve of the lung is affected by both the elastic property of lung tissue and alveolar surface tension. Accumulation of fluid in the interstitium may decrease tissue compliance. It is reported that peroxynitrite injures surfactant protein A, which lowers surface tension and regulates surfactant uptake (35). Furthermore, surfactant activity is known to be suppressed by leakage of interstitial fluid into alveoli (44). Thus, increased alveolar surface tension may strongly affect the P-V curve and cause a downward shift of the P-V curve. Furthermore, increased surface tension may make alveoli unstable and lead to collapse, resulting in an increase in shunt. Thus, physiologic changes observed in LPS-induced lung injury may be caused by both interstitial edema and decreased surfactant function.

The present study demonstrates that in the pathogenesis of ARDS, NO released by iNOS forms peroxynitrite that causes microvascular injury. Both AG and SMT, selective inhibitors of iNOS, prevent pulmonary edema and histologic changes induced by LPS. Inhibitors of iNOS, such as AG and SMT, may have potential in the treatment of sepsis-induced ARDS.

References


