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

Mari Numata,* Shunsuke Suzuki,2* Naoki Miyazawa,* Akira Miyashita,* Yoji Nagashima,† Satoshi Inoue,* Takeshi Kaneko,* and Takao Okubo*

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.

A
cute respiratory distress syndrome (ARDS) remains an important contributor to the morbidity and mortality of patients in intensive care units throughout the world (1). The most common causes are infection, sepsis, aspiration, and trauma. Since trials of anti-inflammatory therapies in ARDS have shown little benefit (2–4), the exact mechanism by which the lungs are injured has been the subject of recent intense investigation.

Nitric oxide (NO) is a highly reactive radical synthesized from the amino acid l-arginine by the action of nitric oxide synthases (NOS) (5). Several isoforms of NOS have been identified and divided into two categories with different regulation and activities (6–8). The constitutive NOS (cNOS) exists in endothelial, neuronal, and various cells, and comprises the low output path on demand in homeostatic processes such as neurotransmission or blood pressure regulation (6, 7). In addition, there are inducible isoforms (iNOS) that may be expressed after exposure to endotoxin and certain cytokines (IL-1, TNF, IFN-γ) in macrophages, neutrophils, mast cells, endothelial cells, and vascular smooth muscle cells (9, 10). Induction of iNOS is a much greater stimulus of NO production than activation of cNOS. Under physiologic states, NO may serve a protective function by scavenging superoxide to protect lung tissues, but the excessive production of NO may contribute to tissue damage in which NO reacts with superoxide to form peroxynitrite, a strong oxidant (11, 12). It is suggested that peroxynitrite is an important oxidant in various diseases (13–15).

Stimulation by LPS induces large amounts of NO and superoxide in alveolar macrophages, lung epithelial, endothelial, and interstitial cells for prolonged periods (6, 8, 11). Overproduction of NO following cytokine- or endotoxin-mediated expression of iNOS can result in shock (16, 17). Endotoxin is reported to trigger the induction of iNOS and form peroxynitrite in the rat aorta (18). A major product from the reaction of peroxynitrite with protein is nitrotyrosine (11, 12). Recently, nitrotyrosine was detected in patients and animals with acute lung injury (19, 20).

We hypothesize that NO generated by iNOS plays a key role in LPS-induced acute lung injury by forming peroxynitrite. To test the hypothesis, we developed an animal model of acute lung injury, comparable physiologically and histologically to human ARDS. We examined, with the use of selective iNOS inhibitors, aminoguanidine (AG) (21, 22) and S-methylisothiourea (SMT) (23), whether NO and peroxynitrite contribute to the development of acute lung injury in LPS-injected animals.

Materials and Methods

Animal preparation

Beagles weighing 10.4 ± 1.7 (SD) kg were used for the experiment. Anesthesia was induced with i.v. thiopental sodium (30 mg/kg), and maintained with the use of pentobarbital sodium (2 mg/kg/h). The animals were intubated with an endotracheal tube and spontaneously breathed room air. Anesthesia was maintained to keep the end-tidal CO2 at approximately 40 mm Hg throughout the experiment. A femoral artery was cannulated with a catheter (8 Fr) for monitoring of systemic arterial pressure and for drawing arterial blood for gas analysis. A Swan-Ganz catheter (131H-8F; Baxter Healthcare, Irvine, CA) was inserted into the main pulmonary artery for measurement of pulmonary hemodynamics. Animals were observed for Copyright © 1998 by The American Association of Immunologists 0022-1767/98/$02.00
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 µg/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/h 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 (PO_{2}) 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 (SaO_{2}) and mixed venous blood (SO_{2}) were measured with a CO-Oximeter (IL-482; Instrumentation Laboratory). Mixed venous samples were collected through a Swan-Ganz catheter. Alveolararterial oxygen difference (A-aDO_{2}) and intrapulmonary shunt ratio (Q_s/Q_t) 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 H_{2}O, 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-480-3; Shinano, Tokyo, Japan) to suppress spontaneous breathing temporarily. The lung volume was increased and then decreased between FRC and TLC in stepwise volume changes of one-sixth of the volume difference from FRC to TLC.

**W/D ratio**

Extravascular 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 x 1 x 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 weight. The blood/tissue 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 H_{2}O 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) containing 0.01% phenylendiamine to prevent fluorescence breaching, and covered with a coverslip. In addition, we tested the staining with nonspecific IgG. Lung sections were observed with a fluorescent 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 x 10^6 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 µm pore size (Neuroprobe) toward human IL-8 (10^{-3} M) or PAF (10^{-6} M) in the well of the lower compartment for 25 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, PaO_{2} decreased gradually during the experiment (p < 0.01 by ANOVA) (Fig. 1). At 24 h after LPS injection, PaO_{2} decreased from 103.6 ± 6.1 mm Hg at 67.4 ± 2.6 mm Hg (p < 0.01). Treatments with AG and SMT prevented the decrease in PaO_{2} in LPS-injected animals, and no changes in PaO_{2} were observed in the control, AG, and SMT groups. A-aDO_{2} 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 mm Hg 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-aDO_{2} by LPS. No change in A-aDO_{2} was observed in the control, AG, and SMT groups. In the LPS group, Q_s/Q_t 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 Q_s/Q_t. 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).
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 intra-alveolar 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 physiologic 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. \(\text{N}^2\)-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 isoform 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 eNOS (21, 22). l-NAME, a nonselective inhibitor of NOS, inhibits endotoxin-induced hypotension (16, 17). In addition, NGH-aminocitrulline, an inhibitor of iNOS, blocks the decrease in MAP by endotoxin (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-n monomethyl-l-lysine) suppressed the production of NO and immunostaining of iNOS (33). This effect on iNOS immunostaining is similar to ours. Recently, Ruettet and Thiemermann have shown that both AG and aminoethyl-isothiourea, 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-NAME and NGH-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


