Inhibition of PARS attenuates endotoxin-induced dysfunction of pulmonary vasorelaxation

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Pulido, Edward J., Brian D. Shames, Craig H. Selzman, Hazel A. Barton, Anirban Banerjee, Denis D. Bensard, and Robert C. McIntyre, J R.. Inhibition of PARS attenuates endotoxin-induced dysfunction of pulmonary vasorelaxation. Am. J. Physiol. 277 (Lung Cell. Mol. Physiol. 21): L769–L776, 1999.—Endotoxin (Etx) causes excessive activation of the nuclear repair enzyme poly(ADP-ribose) synthase (PARS), which depletes cellular energy stores and leads to vascular dysfunction. We hypothesized that PARS inhibition would attenuate injury to mechanisms of pulmonary vasorelaxation in acute lung injury. The purpose of this study was to determine the effect of in vivo PARS inhibition on Etx-induced dysfunction of pulmonary vasorelaxation. Rats received intraperitoneal saline or Etx (Salmonella typhimurium; 20 mg/kg) and one of the PARS inhibitors, 3-aminobenzamide (3-AB; 10 mg/kg) or nicotinamide (Nic; 200 mg/kg), 90 min later. After 6 h, concentration-response curves were determined in isolated pulmonary arterial rings. Etx impaired endothelium-dependent (response to ACh and calcium ionophore) and -independent (sodium nitroprusside) cGMP-mediated vasorelaxation. 3-AB and Nic attenuated Etx-induced impairment of endothelium-dependent and-independent pulmonary vasorelaxation. 3-AB and Nic had no effect on Etx-induced increases in lung myeloperoxidase activity and edema. Lung ATP decreased after Etx but was maintained by 3-AB and Nic. Pulmonary arterial PARS activity increased fivefold after Etx, which 3-AB and Nic prevented. The beneficial effects were not observed with benzoic acid, a structural analog of 3-AB that does not inhibit PARS. Our results suggest that PARS inhibition with 3-AB or Nic improves pulmonary vasorelaxation and preserves lung ATP levels in acute lung injury.

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loration of vascular smooth muscle with the use of the nitric oxide donor sodium nitroprusside (SNP). We also examined the effect of PARS inhibition with 3-AB and Nic in endotoxemia on lung ATP levels and pulmonary arterial PARS activity. A secondary purpose of this study was to determine the effect of 3-AB and Nic on endotoxin-induced lung edema and myeloperoxidase activity as a measure of neutrophil accumulation. The results of this study demonstrate that PARS inhibition with 3-AB and Nic in endotoxemia 1) attenuates dys-function of endothelium-dependent and -independent mechanisms of pulmonary vasorelaxation, 2) has no effect on lung myeloperoxidase activity and edema, and 3) maintains lungATP levels.

MATERIALS AND METHODS

Animal care and housing. All animals received humane care in compliance with the National Research Council's Guide for the Care and Use of Laboratory Animals. Male Sprague-Dawley rats weighing 250–300 g were quarantined in quiet, humidified, light-cycled rooms for 2–3 wk before use. Rats were allowed ad libitum access to food and water throughout quarantine.

Experimental protocol. Rats were administered normal saline (NS; 1 ml ip), endotoxin [Etx; 20 mg/kg ip Salmonella typhimurium lipopolysaccharide (LPS) in 1 ml of NS], a PARS inhibitor alone (3-AB, 10 mg/kg ip, or Nic, 200 mg/kg ip, in 1 ml of NS), or Etx followed by 3-AB or Nic. Rats received 3-AB or Nic 90 min after Etx to avoid any potential interference with inducible nitric oxide synthase (iNOS) induction. The doses of 3-AB and Nic were chosen on the basis of multiple previous in vivo studies employing them in rats (8, 32, 33, 41). A similar set of experiments were performed with the use of a structural analog of 3-AB that does not inhibit PARS [benzoic acid (BA); 10 mg/kg ip]. Rats were provided chow and water ad libitum during the 6-h period after initial injection. No rats died during the 6-h experimental time course. A previous experiment using the same dose of Etx resulted in 15% mortality at 72 h (unpublished data).

Isolated pulmonary arterial ring preparation. Isolated pulmonary arterial rings were harvested, and prepared as previously described (9, 24). Five rats (10 rings) were studied in each group. Rats were anesthetized with pentobarbital sodium (50 mg/kg ip). Median sternotomy was performed, and heparin sulfate (500 USP units) was injected into the right ventricular outflow tract. After removal of the heart and lungs en bloc, the main pulmonary and the right and left pulmonary arteries were excised. The right and left main branch pulmonary arteries were then cut into 3-mm-wide rings; two pulmonary arterial rings were obtained from each rat. Care was taken during this process to avoid endothelial injury.

The pulmonary arterial rings were then placed on 11-mil-gauge steel wires and suspended in individual 10-ml organ chambers containing Earle's balanced salt solution, a standard physiological buffer consisting of CaCl2, 1.80 mM; Na2HPO4 (dibasic), 0.40 mM; D-glucose, 5.50 mM; and NaOH, 19.04 mM. The organ chambers were surrounded by water jackets and continually warmed (37°C). Ring tension was determined by use of a force-displacement transducer (Grass FT03; Grass Instruments, Quincy, MA) attached to each steel wire apparatus. Force displacement was recorded at 0.67 Hz with the use of a MacLab Data Interface Module (ADI Instruments, Milford, MA) on a Macintosh Quadra 650 computer (Apple Computers, Cupertino, CA). Each organ chamber had continual bubbling gas flow at 40 ml/min of 21% O2-5% CO2-74% N2. This produced a Po2 of 100–110 mmHg and a pH of 7.4.

Pulmonary vasorelaxation: concentration-response curves to ACh, A-23187, and SNP. The optimal resting mechanical tension (passive load) for pulmonary rings was determined to be 750 mg in a prior study (9). Rings were suspended at 750 mg and allowed to reach a steady state for 1 h, during which time the Earle's balanced salt solution was changed every 15 min. Rings were preconstricted with phenylephrine (PE) to achieve a PE-induced ring tension between 275 and 325 mg (10−7 M PE). Cumulative concentration-response curves were then generated over the concentration range of 10−9 to 10−4 M (ACh, A-23187, and SNP). For determination of the concentration-response curve, the ring was allowed to reach a steady state before advancing to the next higher concentration. The ring tension remaining in the rings in response to each dose of vasorelaxing agent was expressed in milligrams of tension. PE concentration-response curves were also generated to ensure that endotoxemia did not alter α-adrenergic-mediated vasconstriction.

Lung harvest for myeloperoxidase assay. Pulmonary arterial rings were harvested and prepared as previously described (9). Five lungs from five rats were studied in each group. Lung myeloperoxidase assay. Segments of lung weighing 400–500 g were snap frozen in liquid nitrogen for subsequent determination of myeloperoxidase (MPO) activity. Lung tissue was homogenized for 30 s in 4 ml of 20 mM potassium phosphate buffer, pH 7.4. Lung tissue was quantified with the use of the Coomassie plus protein assay (Pierce, Rockford, IL). The samples were then centrifuged for 30 min at 40,000 g at 4°C (Beckman L-80 Ultracentrifuge; Beckman Instruments, Palo Alto, CA). The pellet was resuspended in 4 ml of 50 mM potassium phosphate buffer, pH 6.0, containing 0.5 g/dl cetrimonium bromide. The samples were sonicated for 90 s with a full-power ultrasonic homogenizer; Cole-Parmer Instruments, Chicago, IL), incubated in a 60°C water bath for 2 h, and centrifuged for 10 min at maximum speed (Eppendorf 5415C; Baxter, San Diego, CA). The supernatant (25 µl) was added to 725 µl of 50 mM phosphate buffer, pH 6.0, containing 0.167 mg/ml diaminidine and 5 × 10−4% hydrogen peroxide. Absorbance of 460-nm visible light was measured between 1 and 3 min (Beckman DU7 spectrophotometer; Beckman Instruments, Irvine, CA). MPO activity (units/mg lung protein) was then calculated as

\[
\text{MPO activity} = \frac{(A_{460})(13.5)}{\text{lungs protein}}
\]

where \(A_{460}\) is the change in absorbance of 460-nm light from 1 to 3 min after the initiation of the reaction. The coefficient 13.5 was empirically determined such that 1 unit of MPO activity is the amount of enzyme that will reduce 1 µmol peroxide/min (3). MPO protein is measured in milligrams.

Lung wet-to-dry weight. Harvested left or right lungs were weighed for determination of wet weight. In separate specimen containers, they were dried over a desiccant (Drierite, Xenia, OH) at 4°C for 5 days to a constant weight and then reweighed.

Lung ATP assay. Lung ATP levels were determined with the use of a quantitative, enzymatic assay (Sigma Diagnostics, St. Louis, MO). Lungs were harvested as described in
Lung harvest for myeloperoxidase assay, wet-to-dry weight determination, and ATP assay, and were immediately frozen with the use of liquid nitrogen. Segments of frozen lung weighing 100–200 mg were ground to a fine powder with the use of mortar and pestle and then sonicated (ultrasonic homogenizer) at full power on ice for 30 s in 1 ml of 12% TCA. (Separate segments of the same lungs were used for quantification of lung protein content as described for lung MPO assay.) The samples were allowed to stand 5 min on ice and were then centrifuged at 750 g for 5 min.

The ATP assay couples a specific phosphorylation reaction requiring ATP (formation of 1,3-diphosphoglycerate) with a dephosphorylation reaction involving the oxidation of NADH. The amount of ATP originally present is equivalent on a molar basis to the amount of NAD formed, which is quantified by measuring the change in absorbance at 340 nm (Beckman DU7 spectrophotometer). The absorbance change is compared with a curve generated from standards of ATP (0, 250, 500, and 1,000 µM) to determine the amount of ATP present. Results are presented as nanomoles of ATP per milligram of lung protein.

Pulmonary arterial PARS activity. PARS activity was measured with the use of a commercially available assay (Genzyme Diagnostics, Cambridge, MA). Four or five pairs of pulmonary arteries were studied in all groups. After dissection of the pulmonary arterial rings from the various experimental groups as for the response to Ach, A-23187, and SNP, the samples were placed on ice in 2 ml of buffer containing 50 mM Tris·Cl (pH 8.0), 25 mM MgCl₂, and 0.1 mM phenylmethanesulfonyl fluoride. The samples were homogenized for 30 s and then sonicated for 20 s at full power (ultrasonic homogenizer). The suspension was centrifuged at 3,000 g for 5 min at 4°C. The protein concentration of the supernatant was determined as described for MPO assay.

Supernatant (the volume containing 20 µg of protein), PARS buffer (10 µl), 1 mM NAD (10 µl), 2 µCi ³²P-labeled NAD (at 1 µCi/µl), and distilled water (the volume required to give a final reaction volume of 100 µl) were mixed in a microcentrifuge tube. The reaction was allowed to proceed at room temperature for exactly 1 min. The reaction was stopped by adding 900 µl of 20% TCA (4°C), and the samples were placed in a microcentrifuge. Enzyme activity was determined by measuring the incorporation of radiolabeled NAD as PARS catalyzed the poly(ADP) ribosylation of proteins. The labeled ADP present was then measured by scintillation counting after TCA precipitation onto a filter. Calculation of PARS activity proceeded as follows

\[
\text{PARS activity} = \frac{\text{total cpm/reaction}}{\text{reaction time} \times \text{vol sample} \times \text{NAD sp act}}
\]

where units are as follows: PARS activity, nmol·min⁻¹·µl⁻¹; reaction time, min; vol (volume of) sample, µl; and NAD specific activity (sp act), counts·min⁻¹·(cpm)·nmol⁻¹. The specific activity of NAD was determined by calculating the total counts in a background control reaction containing 10 nmol of NAD. Results are expressed as picomoles per minute per microliter.

Reagents. Standard reagents as well as the S. typhimurium Etx were obtained from Sigma Chemical (St. Louis, MO), with the exception of A-23187 (Calbiochem, La Jolla, CA). Fresh solutions were prepared daily with either deionized water or NS as the diluent. Concentrations are expressed as final molar concentrations in the organ chambers.

Statistical analysis. Statistical analyses were performed on a Macintosh Quadra computer with StatView software (Brain Power, Calabasas, CA). Data are presented as means ± SE of the number of rings or lungs studied at each point of data collection. In ring experiments, comparisons between groups were made at the same concentrations. Statistical evaluation utilized standard one-way ANOVA with post hoc Bonferroni-Dunn correction. P < 0.05 was accepted as statistically significant.

RESULTS

Effects of PARS inhibition with 3-AB and Nic on Etx-induced impairment of cGMP-mediated pulmonary vasorelaxation. The vasoconstriction response to the α-adrenergic agonist PE is unchanged after Etx (Fig. 1). Etx administration significantly impaired endothelium-dependent, receptor-dependent pulmonary arterial vasorelaxation (response to ACh), and PARS inhibition with 3-AB or Nic attenuated this injury (Fig. 2A). Rings from saline-treated rats were preconstricted with PE to 285 ± 16 mg tension and relaxed to 16 ± 4 mg tension at 10⁻⁶ M ACh, and rings from Etx-treated rats were preconstricted to 283 ± 16 mg tension and relaxed to 168 ± 12 mg tension. In Etx+3-AB and Etx+Nic rats, 106 ± 13 and 66 ± 7 mg PE-induced ring tension remained at 10⁻⁶ M ACh, respectively (P < 0.05 vs. Etx alone, P < 0.05 vs. control).

Endothelium-dependent, receptor-independent cGMP-mediated pulmonary vasorelaxation (response to calcium ionophore A-23187) was significantly impaired after Etx, and both PARS inhibitors were beneficial (Fig. 2B). Control rings were preconstricted to 299 ± 13 mg tension and relaxed to 19 ± 4 mg tension at 10⁻⁶ M A-23187. Rings from Etx-treated rats were preconstricted to 280 ± 8 mg tension, and those from Etx+3-AB and Etx+Nic rats were preconstricted to 283 ± 6 and 288 ± 10 mg tension, respectively. In the Etx-treated rat group, 117 ± 9 mg tension remained in response to 10⁻⁶ M A-23187 compared with 60 ± 9 (Etx+3-AB) and 45 ± 8 (Etx+Nic) mg tension in the
PARS inhibitor groups (P < 0.05 vs. Etx alone, P < 0.05 vs. control).

Endothelium-independent cGMP-mediated vasorelaxation (response to SNP) by direct stimulation of guanylate cyclase was also impaired after Etx treatment, and, again, PARS inhibition with 3-AB and Nic attenuated this dysfunction (Fig. 2). Control rings were preconstricted to 292 ± 8 mg tension, with 4 ± 2 mg tension remaining at 10^{-6} M SNP, and Etx rings were preconstricted to 292 ± 8 mg tension and relaxed to 80 ± 10 mg pressure. PARS inhibition resulted in 22 ± 6 (Etx + 3-AB) and 21 ± 4 (Etx + Nic) mg tension remaining at 10^{-6} M SNP (P < 0.05 vs. Etx alone, P < 0.05 vs. control).

Administration of the PARS inhibitor 3-AB or Nic alone did not affect cGMP-mediated vasorelaxation (data not shown). Neither endothelium-dependent (either receptor-dependent ACh or receptor-independent A-23187) nor endothelium-independent (SNP) vasorelaxation responses were different in comparison with saline-treated control rats.

Administration of BA, a compound that is similar to 3-AB but does not inhibit PARS, had no effect on cGMP-mediated pulmonary vasorelaxation in saline-treated control rats (data not shown). Responses in rings from Etx + BA rats were not different compared with those from Etx-treated rats (P > 0.05 vs. Etx) for both endothelium-dependent and endothelium-independent cGMP-mediated pulmonary vasorelaxation (Fig. 3).

Effects of PARS inhibition with 3-AB and Nic on lung MPO activity in endotoxemia. Etx increased lung MPO activity more than threefold in comparison with control rats, and PARS inhibition with 3-AB or Nic did not

![Fig. 2.](http://ajplung.physiology.org/) Cumulative concentration-response curves to endothelium-dependent and receptor-dependent (response to ACh; A), endothelium-dependent and receptor-independent (response to calcium ionophore A-23187; B), and endothelium-independent (response to SNP; C) cGMP-mediated pulmonary vasorelaxation in isolated pulmonary arterial rings from control, Etx-, Etx + 3-aminobenzamide (Etx + 3-AB), and Etx + nicotinamide (Etx + Nic)-treated rats. 3-AB and Nic administered 90 min after Etx attenuated impairment of both endothelium-dependent and -independent pulmonary vasorelaxation. Values are means ± SE; n = 5 rats/10 rings in each group. *P < 0.05 vs. control and ‡P < 0.05 vs. Etx at same concentration of agonist.

![Fig. 3.](http://ajplung.physiology.org/) Cumulative concentration-response curves to endothelium-dependent and receptor-dependent (response to ACh; A), endothelium-dependent and receptor-independent (response to calcium ionophore A-23187; B), and endothelium-independent (response to SNP; C) cGMP-mediated pulmonary vasorelaxation in isolated pulmonary arterial rings from control, Etx-, and Etx + benzoic acid (Etx + BA)-treated rats. BA is an analog of 3-AB that does not inhibit poly(ADP-ribose) synthase (PARS). BA administered 90 min after Etx had no effect on impairment of endothelium-dependent or -independent vasorelaxation. Values are means ± SE; n = 5 rats/10 rings in each group. *P < 0.05 vs. control at same concentration of agonist.
attenuate this effect (Fig. 4). Lung MPO in controls was 0.21 ± 0.09 units/mg protein. Endotoxemia for 6 h resulted in 0.75 ± 0.07 units MPO/mg protein (P < 0.05 vs. control). Lung MPO activity after Etx and either 3-AB (0.84 ± 0.05 units MPO/mg protein) or Nic (0.65 ± 0.10 units MPO/mg protein) was not different from that in Etx-treated rats (P > 0.05 vs. Etx).

Effects of PARS inhibition with 3-AB and Nic on lung edema after Etx. Lung wet-to-dry weight ratios (W/D) were significantly greater after Etx treatment, and the PARS inhibitors did not demonstrate any beneficial effects (Table 1). Although endotoxemia resulted in an increase in W/D to 4.76 ± 0.03 from the control value of 4.43 ± 0.03 (P < 0.05), neither 3-AB (W/D 4.79 ± 0.03) nor Nic (W/D 4.80 ± 0.05) attenuated this injury (P > 0.05 vs. Etx).

Effect of PARS inhibition with 3-AB and Nic on lung ATP levels in endotoxemia. The Etx-induced decrease in lung ATP levels at 6 h was prevented by PARS inhibition with 3-AB and Nic (Fig. 5). Etx reduced lung ATP from the control value of 13.39 ± 0.29 to 8.64 ± 0.31 nmol/mg protein (P < 0.05). Etx+3-AB-treated rats had lung ATP levels similar to those of control rats (12.47 ± 0.50 nmol/mg protein, P = 0.20) that were also different from those of rats treated with Etx alone (P < 0.05). The lung ATP levels of Etx+Nic-treated rats were also similar to those of saline-treated rats (13.65 ± 0.69 nmol/mg protein, P = 0.74 vs. control) and different from those of rats treated with Etx alone (P < 0.05). 3-AB or Nic alone had no effect on lung ATP levels in saline-treated rats (data not shown). The lung ATP levels of Etx+BA-treated rats (8.02 ± 0.33 nmol/mg protein) were not different from those of Etx-treated rats (P = 0.37).

Effect of PARS inhibition with 3-AB and Nic after Etx on pulmonary arterial PARS activity. Pulmonary PARS activity increased more than fivefold after Etx treatment, and the PARS inhibitors 3-AB and Nic prevented this increase (Fig. 6). Etx increased pulmonary arterial PARS activity from the control value of 0.188 ± 0.010 pmol·min⁻¹·µl⁻¹ to 1.050 ± 0.047 pmol·min⁻¹·µl⁻¹ (P < 0.05). The pulmonary arteries from Etx+3-AB-treated rats had PARS activity similar to those of control rats (0.176 ± 0.015 pmol·min⁻¹·µl⁻¹, P = 0.83) and different from rats treated with Etx alone (P < 0.05). Similarly, the pulmonary arterial PARS activity of Etx+Nic-treated rats (0.236 ± 0.072 pmol·min⁻¹·µl⁻¹) was not different from control (P = 0.48) but was different from Etx alone (P < 0.05). Neither 3-AB nor Nic alone affected pulmonary arterial PARS activity in saline-treated rats (data not shown). The pulmonary arterial PARS activity of Etx+BA-treated rats (0.951 ± 0.148 pmol·min⁻¹·µl⁻¹) was not different from that of Etx-treated rats (P = 0.32).

**DISCUSSION**

We found that PARS inhibition with 3-AB and Nic in endotoxemia attenuates the dysfunction of cGMP-mediated pulmonary vasorelaxation and does not affect lung MPO activity and edema but maintains lung ATP levels. Although other studies have demonstrated beneficial effects of PARS inhibitors on the systemic vascular dysfunction in endotoxic shock (27, 32, 39, 41), this is the first study to our knowledge that examines the effect of in vivo PARS inhibition on the Etx-induced impairment of pulmonary arterial vasorelaxation. Two distinct PARS inhibitors, 3-AB and Nic, ameliorated the Etx-induced impairment of both endothelium-dependent and -independent mechanisms of pulmonary vasorelaxation. The prototypical, competitive PARS inhibitor 3-AB does not directly scavenge peroxynitrite (32) and does not prevent the development of DNA strand breakage (40). The beneficial effects of 3-AB appear to be related to PARS inhibition as opposed to other possible pharmacological properties of this drug. Its inactive analog, benzoic acid, did not affect the Etx-induced dysfunction of pulmonary vasorelaxation. PARS generates Nic in its enzymatic catalyzation of the transfer of ADP-ribose to various proteins.

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**Table 1. Lung wet-to-dry weight ratios**

<table>
<thead>
<tr>
<th>Experimental Group</th>
<th>Lung W/D</th>
<th>P Value vs. Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4.43 ± 0.03</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Etx</td>
<td>4.76 ± 0.03*</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Etx+3-AB</td>
<td>4.79 ± 0.03*</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>3-AB</td>
<td>4.46 ± 0.03</td>
<td>0.52</td>
</tr>
<tr>
<td>Etx+Nic</td>
<td>4.80 ± 0.05*</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Nic</td>
<td>4.42 ± 0.05</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 5 rats/group. Values are lung wet-to-dry weight ratios (W/D) in control, endotoxin (Etx), Etx+3-aminobenzamide (Etx+3-AB), 3-AB (alone), Etx+nicotinamide (Etx+Nic), and Nic (alone)-treated rats. Etx caused a significant increase in lung edema (*P < 0.05 vs. control). In vivo administration of poly(ADP-ribose) synthetase inhibitors 3-AB and Nic 90 min after Etx did not affect increase in lung edema (P > 0.05 vs. Etx alone).
Therefore, Nic can decrease PARS activity through negative feedback. Its beneficial effect may also stem from conversion back to NAD$^+$, thus directly restoring cellular energy levels (41). Although Nic is somewhat less specific than 3-AB, both compounds are potent inhibitors of PARS activity (2). In vivo administration of PARS inhibitors 3-AB and Nic 90 min after Etx prevented decrease in lung ATP ($* P < 0.05$ vs. Etx alone and $P > 0.05$ vs. control). BA, a structural analog of 3-AB that does not inhibit PARS, did not affect a decrease in lung ATP after Etx.

We administered the PARS inhibitors after endotoxemia was established for two reasons. This model approximates the clinical scenario of sepsis, and we also minimized any possible effect 3-AB and Nic may have on iNOS upregulation. Although it has been demonstrated that PARS acts to enhance iNOS gene transcription in vitro (19) and prevents tumor necrosis factor-α-stimulated induction of iNOS in a mouse fibroblast cell line (10), other investigators have demonstrated minimal or no effects by PARS inhibitors on in vitro (40) and in vivo (36) nitric oxide production after LPS. The PARS inhibitors 3-AB and Nic can have additional effects depending on the cell type or system studied (28). Benzamide analogs scavenge hydroxyl radical but not nitric oxide or peroxynitrite. These compounds can inhibit the expression of adhesion molecules, inhibit the cytochrome P-450 enzymes, and either stimulate or inhibit apoptosis. Nic has also been shown to scavenge oxyradicals and inhibit adhesion receptor expression (28).

In the current study, we found that PARS inhibition with 3-AB and Nic had no effect on Etx-induced lung MPO activity. Previous work in our laboratory (24) has demonstrated the importance of the neutrophil in this model of Etx-induced dysfunction of pulmonary vasorelaxation. Neutrophil depletion with the use of vinblastine or rabbit anti-rat neutrophil antisera before Etx attenuated the impairment of the response to cGMP-mediated pulmonary vasorelaxation. However, neutrophil depletion did not totally eliminate the dysfunction of pulmonary arterial vasorelaxation. Thus there exist neutrophil-independent mechanisms of vasomotor dysfunction in Etx-induced acute lung injury, and increased PARS activity may be one of these mechanisms contributing to vascular dysfunction. Our results agree with a recent study that also found no effect of 3-AB on Etx-induced increases in rat lung and ileum MPO activity (26). In contrast to our findings, Szabo et al. (26) found a reduction in pulmonary microvascular leakage in 3-AB-treated rats. These results may be explained by the fact that a pretreatment as well as a posttreatment dose of 3-AB was utilized. Perhaps the Etx-induced increase in the lung wet-to-dry ratio is mediated by an early, PARS-dependent mechanism.

In contrast, PARS inhibition decreased neutrophil recruitment in other models of non-Etx-mediated inflammation. The PARS inhibitor 3-AB reduced myocardial neutrophil accumulation after ischemia-reperfusion injury (38), and studies in PARS$^{-/-}$ mice demonstrated a role for this enzyme in the regulation of the adhesion molecules P-selectin and intercellular adhesion molecule-1 (42). Szabo et al. (29) recently found that PARS inhibition with 3-AB prevented both local and systemic inflammation after carrageenan or zymosan challenge. The protective effects appeared to be more pronounced in the severe forms and delayed phase of inflammation, and inhibition of PARS increased the rate of adherent neutrophil detachment.
from the endothelium. In these nonendotoxia models, PARS inhibitors were administered before the inflammatory stimulus, suggesting that an early PARS-dependent mechanism is involved in neutrophil accumulation and edema. The lack of effect by 3-AB and Nic on the Etx-induced increase in MPO activity in the current study and in the study by Szabo et al. (26) suggests that lung neutrophil recruitment in severe endotoxia may be mediated by a PARS-independent step. Further investigation is needed to establish the effect of PARS inhibition on neutrophil accumulation and function in endotoxia.

We further examined the role of PARS in Etx-induced acute lung injury by measuring lung ATP levels and pulmonary arterial PARS activity. The maintenance of lung tissue ATP levels after 3-AB treatment in endotoxia suggests that PARS activation may be an important pathway in the reduction of cellular energy levels in this model of lung injury. However, lung ATP levels may not accurately represent pulmonary vascular energy status, but previous studies suggest that endotoxia depletes cellular energy levels and that this energy deficit may be linked to a dysfunction of pulmonary arterial vasorelaxation. In rat aortic smooth muscle cells, the PARS inhibitors 3-AB, Nic, and PD-128763 inhibited the reduction in cellular NAD+ and ATP as well as the suppression of mitochondrial respiration in response to LPS and interferon-γ stimulation (32). Rodman et al. (20) found that inhibitors of oxidative phosphorylation reduced receptor-dependent relaxation in both aortic and pulmonary arterial rings. In vivo administration of both 3-AB and Nic prevented the Etx-induced increase in pulmonary arterial PARS activity, confirming the action of the inhibitors in the tissue with which we performed our vasorelaxation experiments. Furthermore, benzoic acid, a compound that is structurally similar to 3-AB but does not inhibit PARS, had no effect on lung ATP levels, pulmonary arterial PARS activity, or the dysfunction of pulmonary vasorelaxation in endotoxia.

Peroxynitrite formation is the proposed initial stimulus leading to PARS activation, with subsequent impairment of cellular energetics and vascular function in endotoxia (32, 39, 40). Although the presence of peroxynitrite in the lungs has been demonstrated experimentally in Escherichia coli Etx-treated rats (34) and clinically in autopsy specimens from patients with sepsis-induced pulmonary injury (15), its role in the pulmonary circulation remains unclear. Other investigators have found that peroxynitrite itself is a direct pulmonary arterial vasodilator in the dose range of 10–100 µM (6, 37). However, this observed effect of peroxynitrite occurs at concentrations that are not physiologically relevant because peroxynitrite would occur in the nanomolar range even in disease states (17). Although PARS activity was not measured directly, Chabot et al. (6) found an inhibitory effect of 3-AB on this peroxynitrite-induced vasodilation. However, the effective dose of 3-AB was 10 mM, and a dose of 1 mM 3-AB did not affect the vasodilation to peroxynitrite. The high concentration of 3-AB needed to observe inhibition calls into question the specificity of this dose on PARS activity. The published IC50 of 3-AB is 33 µM, with 88% inhibition of PARS occurring at 1 mM (2). Although peroxynitrite may not be the stimulus for pulmonary arterial PARS activation, hydroxyl radical, a species also present in endotoxia, can cause PARS activation and subsequent endothelial damage (1, 14). Further work is needed to define the relative roles of peroxynitrite and hydroxyl radical in PARS activation and vascular injury.

Although both pulmonary arterial PARS activity and lung ATP levels returned to control values with 3-AB administration, the Etx-induced dysfunction in cGMP-mediated vasorelaxation was only partially attenuated. PARS-independent mechanisms of vascular dysfunction may also contribute to the injury, as has been observed in other models of inflammation (11, 32). Cellular damage in oxidative stress occurs by parallel and/or synergistic pathways, which may or may not involve peroxynitrite generation and PARS activation. Indeed, inhibition of PARS represents just one potential strategy to reduce nitric oxide- or peroxynitrite-mediated cellular injury. Other agents such as specific inhibitors of iNOS, superoxide dismutase mimetics, and scavengers of peroxynitrite also offer promise in the therapy of shock and other inflammatory diseases. In summary, we found that the PARS inhibitors 3-AB and Nic in Etx-induced acute lung injury attenuate the dysfunction of pulmonary vasoconstriction and maintain lung ATP levels but do not affect lung MPO activity and edema. The data presented here suggest that PARS activation in endotoxia contributes to the development of pulmonary vascular dysfunction. PARS inhibition may provide a novel therapeutic approach in ameliorating the vascular dysfunction seen in sepsis and acute lung injury.

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