HIGHLIGHTED TOPIC | Lung Growth and Repair

Pentoxifylline reduces fibrin deposition and prolongs survival in neonatal hyperoxic lung injury

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Bronchopulmonary dysplasia (BPD) is a leading cause of mortality and morbidity in preterm infants despite improved treatment modalities. Pentoxifylline, a phosphodiesterase inhibitor, inhibits multiple processes that lead to neonatal hyperoxic lung injury, including inflammation, coagulation, and edema. Using a preterm rat model, we investigated the effects of pentoxifylline on hyperoxia-induced lung injury and survival. Preterm rat pups were exposed to 100% oxygen and injected subcutaneously with 0.9% saline or 75 mg/kg pentoxifylline twice a day. On day 10, lung tissue was harvested for histology, fibrin deposition, and mRNA expression, and bronchoalveolar lavage fluid was collected for total protein concentration. Pentoxifylline treatment increased mean survival by 3 days (P = 0.0018) and reduced fibrin deposition by 66% (P < 0.001) in lung homogenates compared with untreated hyperoxia-exposed controls. Monocyte chemoattractant protein-1 expression in lung homogenates was decreased, but the expressions of TNF-α, IL-6, matrix metalloproteinase-12, tissue factor, and plasminogen activator inhibitor-1 were similar in both groups. Total protein concentration in bronchoalveolar lavage fluid was decreased by 33% (P = 0.029) in the pentoxifylline group. Pentoxifylline treatment attenuates alveolar fibrin deposition and prolongs survival in preterm rat pups with neonatal hyperoxic lung injury, probably by reducing capillary-alveolar protein leakage.

hyperoxia; inflammation; coagulation; newborn rat; bronchopulmonary dysplasia

Bronchopulmonary dysplasia (BPD) is a leading cause of mortality and morbidity in preterm newborn infants with respiratory distress syndrome despite improved treatment modalities (22). Nowadays, BPD, defined by oxygen requirement at 36 wk of gestation, affects especially newborn infants born at <30 wk of gestation with a birth weight <1,200 g (1, 13). BPD is a multifactorial disease, characterized by decreased alveolarization and abnormal vascularization and associated with oxidative stress, barotrauma, surfactant deficiency, inflammation, alveolar fibrin deposition, nutrition, and genetic background (13–15). The (im)balance between initiating factors and host characteristics probably determines whether BPD will actually occur in the preterm infant.

The inflammatory response and coagulation cascade play important roles in the pathophysiology of acute and chronic lung disease in newborn infants and animal models. Increased levels of proinflammatory cytokines (TNF-α and IL-6) have been observed in tracheal aspirates of infants developing BPD (16–18). In addition, intra-alveolar and intravascular fibrin deposition has been detected in acute lung injury (2, 10, 11). In animal models, including premature baboons and neonatal mice and rats, exposure to hyperoxia results in chronic lung disease closely resembling BPD in preterm infants (3, 5, 8, 28, 37, 39).

In a previous study (37), our group demonstrated that genes involved in inflammation, coagulation, fibrinolysis, fibrosis, extracellular matrix turnover, alveolar development, edema, cell cycle, and oxidative stress response are differentially expressed in preterm rats with BPD secondary to exposure to hyperoxia (37). Expression profiles were in line with histopathology. The importance of extravascular fibrin deposition and upregulation of the coagulation cascade and inflammatory response in this model suggests a potential role for compounds with anti-inflammatory and anticoagulant properties. The methylxantine derivative pentoxifylline (PTX) has been used in the treatment of peripheral arterial diseases because of its positive effects on the capillary blood flow by reducing blood viscosity and improving erythrocyte deformability (27, 38). Moreover, PTX, a phosphodiesterase inhibitor, has significant anti-inflammatory effects, resulting in accumulation of intracellular CAMP. PTX decreases neutrophil sequestration, prevents the pulmonary vascular permeability to protein (12, 41, 43), and inhibits the production of free oxygen radicals (33). The inhibitory effect of PTX on proinflammatory responses and diffuse intravascular coagulation was demonstrated in baboons with lipopolysaccharide-induced endotoxemia (23). PTX was also effective in a radiation-induced lung model in...
mice by inhibiting TNF-α mRNA and protein production in lung tissue (29). Modulatory effects of PTX on the production of IL-6 were demonstrated in fetal rat type II pneumocytes exposed to hyperoxia and nitric oxide (6).

Because PTX inhibits multiple processes that contribute to the development of BPD, including inflammation, coagulation, and edema, we investigated the effects of PTX treatment on hyperoxia-induced lung injury. We demonstrate that PTX treatment in an experimental model of neonatal hyperoxic lung injury reduces extravascular fibrin deposition and prolongs survival.

MATERIALS AND METHODS

Animals. Timed-pregnant Wistar rats were kept in a 12:12-h dark-light cycle and fed a standard chow diet (Special Diet Services, Witham, Essex, UK) ad libitum. After a gestation of 21.5 days (spontaneous birth occurs 22 days after conception), pregnant rats were killed by decapitation and pups were delivered by hysterectomy through a median abdominal incision. Immediately after birth, pups were dried and stimulated. Pups from two to three litters, with a maximum of 12 pups, were pooled and exposed to 100% oxygen in a transparent 50-cm3 jar after birth. The oxygen concentration, weight, evidence of life, and survival experiments. Pups were fed by lactating foster rats. To avoid oxygen toxicity of the foster rats, two groups of five pups exposed to room air were included and used to generate data on room air-exposed controls. Foster rats were rotated daily between the three cages. The oxygen concentration, weight, evidence of life, and survival experiments. Pups were fed by lactating foster rats. To avoid oxygen toxicity of the foster rats, two groups of five pups exposed to room air were included and used to generate data on room air-exposed controls. Foster rats were rotated daily between the three cages. The oxygen concentration, weight, evidence of life, and survival experiments. Pups were fed by lactating foster rats. To avoid oxygen toxicity of the foster rats, two groups of five pups exposed to room air were included and used to generate data on room air-exposed controls. Foster rats were rotated daily between the three cages.
with the ABI Prism 7700 sequence detection system version 1.9 software and quantified with the comparative threshold cycle method with β-actin as a housekeeping gene reference (26).

**Protein assay.** Total protein concentration was measured in bronchoalveolar lavage fluid (BALF) using the DC protein assay (Bio-Rad), according to the manufacturer’s instructions. The detection limit was 31 μg/ml.

**Statistical analysis.** Values are expressed as means ± SE. Differences between groups were analyzed with the Student’s t-test. For comparison of survival curves, Kaplan-Meier analysis followed by a log rank test was performed. P values of <0.05 were considered statistically significant.

**RESULTS**

**Fibrin deposition.** Because fibrin deposition correlates well with the severity of tissue damage in hyperoxia-induced lung injury, we quantified fibrin deposition by Western blot analysis in lungs after exposure to different oxygen concentrations to determine the optimal experimental conditions for intervention. Fibrin deposition in lung homogenates of preterm rat pups exposed to 60, 80, and 100% oxygen is shown in Fig. 1A. Significant fibrin deposition was absent in lungs of pups exposed to 60 and 80% oxygen for 14 days (Fig. 1B). However, fibrin deposition increased from 18 ± 8 in room air-exposed pups to 296 ± 42 ng fibrin/mg of tissue in lungs of pups exposed to 100% oxygen for 10 days (Fig. 1B; P < 0.001), demonstrating that this is the optimal experimental condition. Therefore, intervention studies were performed in preterm rat pups exposed to 100% oxygen. Treatment of oxygen-exposed pups with PTX for 10 days resulted in a reduction of fibrin deposition from 296 ± 42 in oxygen-exposed pups treated with 0.9% saline (black bars) to 80 ± 42 in lungs of pups exposed to 100% oxygen (gray bars). However, fibrin deposition in lungs of pups exposed to 100% oxygen was not significantly different from lungs of room air-exposed pups treated with PTX (Fig. 1B).

**Table 1. Sequences of oligonucleotides used as forward and reverse primers for real-time RT-PCR.**

<table>
<thead>
<tr>
<th>Gene Product</th>
<th>Forward Primer</th>
<th>Reverse Primer</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL-6</td>
<td>5’-ATAATGTTCTCAGGAGATCTTTGGA-3’</td>
<td>5’-TGATATCATGCTTGGATACAA-3’</td>
</tr>
<tr>
<td>MCP-1</td>
<td>5’-TGCGGAAACCTGAGCTAGACAA-3’</td>
<td>5’-ACGTCCGAGTTCAGCATGCT-3’</td>
</tr>
<tr>
<td>MMP-12</td>
<td>5’-TGCTCTCTGCTGCTGAGCAGTACAA-3’</td>
<td>5’-GGGTTTCTGAGGATGTTGTTTT-3’</td>
</tr>
<tr>
<td>PAI-1</td>
<td>5’-AGCTGGGAGATCTGACATCTG-3’</td>
<td>5’-GCTGCTCTCTGCTGCAAAAGA-3’</td>
</tr>
<tr>
<td>TF</td>
<td>5’-CCGAGAAGGACCTACCAAGATG-3’</td>
<td>5’-TGTCGCAAAATGATGAGATTT-3’</td>
</tr>
<tr>
<td>β-actin</td>
<td>5’-TTCAACACCCCAGCCATGT-3</td>
<td>5’-AGTGGTAAGACCAGAGGCAATCG-3’</td>
</tr>
</tbody>
</table>

MCP, monocyte chemoattractant protein; MMP, matrix metalloproteinase; PAI, plasminogen activator inhibitor; TF, tissue factor.

**Fig. 1. A:** Western blot analysis of fibrin deposition in lung homogenates of preterm rat pups exposed to 60 and 80% oxygen for 14 days and 100% oxygen for 10 days. RA, room air control; C, oxygen-exposed pup treated with 0.9% saline; P, oxygen-exposed pup treated with pentoxifylline (PTX). Lung homogenates of pups exposed to 60 and 80% oxygen were not diluted, whereas lung homogenates of pups exposed to 100% oxygen were diluted 1:5. Fibrin standards were used to quantify fibrin deposition in the lung homogenates. **B:** quantification of fibrin deposition in lung homogenates on day 10. Experimental groups include room air controls (white bars), oxygen-exposed pups treated with 0.9% saline (black bars), and oxygen-exposed pups treated with PTX (gray bars). Oxygen-treated pups were exposed to 60% oxygen (n = 4), 80% oxygen (n = 4), and 100% oxygen (n = 20). Data are expressed as means ± SE. **P < 0.001, oxygen vs. room air-exposed controls. **P < 0.001, PTX vs. oxygen-exposed controls. C and D: formaldehyde-fixed paraffin lung section, 400-fold magnification, of a rat pup exposed to room air for 10 days (C) and after exposure to 100% oxygen for 10 days (D). Sections were immunohistochemically stained with monoclonal anti-human fibrin antibody 59D8, which specifically detects rat β-fibrin. Arrows in D indicate fibrin deposits in the alveolar lumen of the lung.
exposed controls to $100 \pm 23$ ng fibrin/mg of tissue in lungs of PTX-treated pups exposed to 100% oxygen (Fig. 1B; $P < 0.001$). The localization of fibrin deposits in the lungs was studied immunohistochemically on formaldehyde-fixed paraffin sections. Fibrin deposits were mainly observed in the extravascular compartment in the alveolar lumen and were associated with the alveolar wall (Fig. 1D). In control lungs, fibrin deposits were absent (Fig. 1C).

mRNA expression in lung homogenates. Because PTX has anti-inflammatory, anti-coagulant and anti-fibrinolytic properties, we studied mRNA expression of key enzymes involved in these processes in lung homogenates after lung injury by hyperoxia. TNF-α mRNA expression did not change after oxygen exposure ($P = 0.934$) or PTX treatment ($P = 0.35$; Fig. 2A). IL-6 ($P < 0.001$), matrix metalloproteinase-12 (MMP-12; $P = 0.019$), and monocyte chemoattractant protein-1 (MCP-1; $P < 0.001$) expressions after 10 days of hyperoxia were increased compared with room air-exposed controls (Fig. 2A). IL-6 expression ($P = 0.55$) and MMP-12 expression ($P = 0.29$) did not change by PTX treatment during oxygen exposure (Fig. 2A). However, MCP-1 mRNA expression decreased 1.6-fold in pups exposed to hyperoxia and 10 days of PTX treatment (Fig. 2A; $P = 0.036$). The expression of the physiological initiator of coagulation tissue factor (TF; $P = 0.008$) and the anti-fibrinolytic factor plasminogen activator inhibitor-1 (PAI-1; $P < 0.001$) increased during exposure to hyperoxia compared with room air-exposed controls (Fig. 2B). However, PTX treatment did not change TF ($P = 0.20$) and PAI-1 ($P = 0.93$) expression after exposure to 100% oxygen for 10 days (Fig. 2B).

BALF. Total protein concentration was measured in BALF as a marker for capillary leakage. Protein concentration on postnatal day 10 was $103 \pm 7 \mu g/ml$ in pups exposed to room air, $328 \pm 37 \mu g/ml$ in pups exposed to 100% oxygen treated with saline (Fig. 3; $P < 0.001$), and $218 \pm 18 \mu g/ml$ in pups exposed to 100% oxygen treated with PTX (Fig. 3; $P = 0.029$). PTX treatment decreased the white blood cell count in BALF from $55 \pm 16 \times 10^3$ cells/ml in oxygen-exposed pups treated with saline to $16 \pm 5 \times 10^3$ cells/ml in oxygen-exposed pups treated with PTX ($P = 0.05$).

Survival. Survival of PTX-treated hyperoxia-exposed pups was prolonged compared with oxygen-exposed controls (Fig. 4; $P = 0.0018$). After 12 days of oxygen exposure, 73% of the controls had died vs. only 20% of the PTX pups. The mean survival of preterm oxygen-exposed rat pups treated with PTX was prolonged by 3 days. Subcutaneous injection of room air-exposed pups ($n = 5$) with 0.9% saline did not lead to illness or mortality the first 4 wk after birth (data not shown).

DISCUSSION

The reported experiments show that PTX treatment reduces fibrin deposition threefold and prolongs survival by 3 days in preterm rat pups with hyperoxia-induced lung injury. Fibrin deposition is an important contributor to the pathogenesis of lung injury by oxidative stress. The findings of this study suggest that inhibition of fibrin deposition may have therapeutic potential in the treatment of BPD. This hypothesis is supported by studies in PAI-1 knockout mice, which have less hyperoxia-induced fibrin deposition, resulting in a less severe
phenotype and increased resistance toward hyperoxia-induced mortality (2). In addition, blocking of the coagulation cascade attenuates acute lung injury induced by gram-negative sepsis in baboons (4). Fibrin may have proinflammatory and profibrinolytic properties, by facilitating cell migration and activating inflammatory cells and fibroblasts (31), and it hampers pulmonary gas exchange via inactivation of lung surfactant (7, 30).

Because the mechanism by which PTX reduces fibrin deposition and prolongs survival can be multifactorial, we studied the mRNA expression of key enzymes involved in inflammation, coagulation, and fibrinolysis. PTX reduced MCP-1 mRNA expression but not the expression of TNF-α, IL-6, and MMP-12, indicating that only the influx of monocytes and macrophages to the lung is inhibited during the inflammatory response. PTX did not reduce mRNA expression of TF and PAI-1, indicating that transcriptional activation of the coagulation cascade and inhibition of the fibrinolytic cascade are minor. Because fibrin deposits are located in the extravascular compartment in alveolar septa and lumen, extravasation of plasma proteins, including fibrinogen, into the alveolar lumen may be important. This is supported by a decrease in protein concentration in BALF after PTX treatment, indicating that extravasation of plasma proteins is inhibited by PTX, probably resulting in a lower fibrinogen content in the alveolar fluid and, as a result, less fibrin deposition.

Conflicting results have been found on survival after PTX treatment in lung injury models. In contrast to our findings, PTX treatment did not prolong survival in adult rats after exposure to >95% oxygen (25). This discrepancy may be explained by the difference in oxygen tolerance between neonates and adults in combination with a lower PTX dosage used in the adult rat experiments. Beneficial effects of PTX treatment on survival were reported after endotoxemia, even at low dosages, in mice (42).

We only found an effect of PTX on MCP-1 mRNA expression but not on TNF-α and IL-6 expression. Many other in vitro and in vivo studies demonstrate that PTX inhibits the expression of proinflammatory cytokines (6, 19, 23, 24, 29, 32, 34, 35, 42). These studies emphasize the attenuating effect of PTX on TNF-α and IL-6, the key proinflammatory targets of PTX. Moreover, three studies implicate that inhibition of the release of TNF-α is the most important outcome predictor in endotoxemia (24, 34, 42). A possible explanation for this discrepancy might be that TNF-α does not play the same pivotal role in the inflammatory response in neonatal hyperoxia-induced lung injury as it does in endotoxemia. The finding that TNF-α was not significantly different between room air-exposed and oxygen-exposed pups strengthens this hypothesis. In contrast, the importance of MCP-1 has been demonstrated in a hyperoxia-induced BPD model. Newborn rats exposed to hyperoxia were injected with anti-MCP-1, resulting in the prevention of neutrophil influx and reduced protein oxidation (36). We assume that the inhibitory effect of PTX on the expression of MCP-1 results in a reduction of the influx of macrophages and/or neutrophils to the lung, resulting in less tissue damage and contributing to an improvement in BPD.

The clinical importance of PTX treatment was recently demonstrated by preliminary data on preterm neonates, prone to develop BPD, in whom pretreatment with 40–80 mg·kg⁻¹·day⁻¹ of nebulized PTX in four dosages reduced treatment requirements after the first month of life (21). Limitations of the potential clinical importance of our observations are the high oxygen concentration (100%) used for a prolonged period (10 days) to induce lung injury and the relatively high PTX concentration compared with dosages used in the clinic: 150 mg·kg⁻¹·day⁻¹ subcutaneously in our study vs. 40–80 mg·kg⁻¹·day⁻¹ by nebulization and 30 mg·kg⁻¹·day⁻¹ intravenously in preterm human infants (20, 21). Furthermore, few human preterm infants will be exposed to 100% oxygen for 10 days, but less extreme oxygen exposures did not produce the primary indicator of injury (fibrin deposition) in the animal model used in this study.

In summary, this study shows that PTX significantly prolongs survival and attenuates alveolar fibrin deposition of preterm rat pups with experimental neonatal hyperoxic lung injury. The effect of PTX is probably the result of decreased protein leakage from the capillaries to the alveolar lumen. PTX may have the potential to prevent and/or reduce the severity of BPD in preterm infants who need ventilatory support in the neonatal intensive care unit.

GRANTS
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