Respiratory Infection

PAI-1 is an essential component of the pulmonary host response during *Pseudomonas aeruginosa* pneumonia in mice

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**ABSTRACT**

**Rationale** Elevated plasma and bronchoalveolar lavage fluid plasminogen activator inhibitor 1 (PAI-1) levels are associated with adverse clinical outcome in patients with pneumonia caused by *Pseudomonas aeruginosa*. However, whether PAI-1 plays a pathogenic role in the breakdown of the alveolar—capillary barrier caused by *P aeruginosa* is unknown.

**Objectives** The role of PAI-1 in pulmonary host defence and survival during *P aeruginosa* pneumonia in mice was tested. The in vitro mechanisms by which *P aeruginosa* causes PAI-1 gene and protein expression in lung endothelial and epithelial cells were also examined.

**Methods and results** PAI-1 null and wild-type mice that were pretreated with the PAI-1 inhibitor Tiplaxtinin had a significantly lower increase in lung vascular permeability than wild-type littermates after the airspace instillation of 1×10⁷ colony-forming units (CFU) of *P aeruginosa* bacteria. Furthermore, *P aeruginosa* in vitro induced the expression of the PAI-1 gene and protein in a TLR4/p38/RhoA/NF-kB (Toll-like receptor 4/p38/RhoA/nuclear factor-kB) manner in lung endothelial and alveolar epithelial cells. However, in vivo disruption of PAI-1 signalling was associated with higher mortality at 24 h secondary to decreased neutrophil migration into the distal airspace in response to *P aeruginosa*.

**Conclusions** The results indicate that PAI-1 is a critical mediator that controls the development of the early lung inflammation that is required for the activation of the later innate immune response necessary for the eradication of *P aeruginosa* from the distal airspaces of the lung.

**Key messages**

What is the key question?

- The role of PAI-1 in pulmonary host defence and survival during *P aeruginosa* pneumonia in mice is not known.

What is the bottom line?

- PAI-1 is a critical mediator that controls the development of the early lung inflammation that is required for the activation of the later innate immune response necessary for the eradication of *P aeruginosa* from the distal airspaces of the lung.

Why read on?

- Although associated with an early attenuation of the severity of pulmonary oedema formation, in vivo disruption of PAI-1 signalling is associated with higher mortality at 24 h secondary to decreased neutrophil migration into the distal airspace in response to *P aeruginosa*.

**INTRODUCTION**

*Pseudomonas aeruginosa* is an opportunistic pathogen that causes lethal pneumonia in immunocompromised individuals and in critically ill patients.¹ ² *P aeruginosa* pneumonia is characterised by a shift in the balance between procoagulant and anticoagulant/fibrinolytic activity in the alveoli followed by intra-alveolar fibrin deposition. Early procoagulant activity in the alveolar space may exert beneficial effects by decreasing the protein leakage through the alveolar—capillary barrier caused by *P aeruginosa*. However, excessive fibrin deposition causes deleterious effects by increasing the lung inflammatory response and vascular permeability. When fibrin is present in the alveolar space, it is usually degraded by plasmin, a proteolytic enzyme that is present in the lung tissue as an inactive zymogen. However, decreased fibrinolytic activity has been reported in the airspaces of the lungs of patients with *P aeruginosa* pneumonia.₃

The plasminogen activator inhibitor 1 (PAI-1), a member of the serine protease inhibitors superfamily,⁴ which is expressed by endothelial cells, epithelial cells, monocytes and macrophages, is the principal inhibitor of tissue-type plasminogen activator (tPA) and urokinase-type plasminogen activator (uPA) and thus inhibits fibrinolysis. PAI-1 levels have been shown to be elevated in the airspace and plasma of patients with ventilator-associated pneumonia (VAP), aspiration pneumonia and acute lung injury (ALI),⁵ ⁶ ⁷ and to correlate with severe disease and adverse clinical outcome.⁸ Furthermore, bronchoalveolar lavage (BAL) fluid levels of PAI-1 are higher in patients with *P aeruginosa*-induced VAP than those found in other infections⁹ and increased BAL levels of PAI-1 were associated with increased mortality in a cohort of intensive care patients with *P aeruginosa* VAP,¹⁰ suggesting a role for PAI-1 in the development of severe *P aeruginosa* VAP. However, these clinical associations do not establish a direct causal link between PAI-1 and the development of more severe *P aeruginosa* pneumonia, particularly because...
contrasting results have been reported with PAI-1 gene deletion in several experimental models of bacterial pneumonia in mice.\textsuperscript{11, 12} PAI-1 gene deletion has also been shown to be protective in non-infectious experimental models of lung injury induced by ischaemia–reperfusion or hyperoxia.\textsuperscript{13, 14} Thus, it is not clear whether PAI-1 itself is beneficial or deleterious for the host during \textit{P aeruginosa} pneumonia, and answering this question constitutes the goal of the present study.

**MATERIAL AND METHODS**

More details are available in the online supplement.

**Reagents**

All cell culture media were prepared by the University of California San Francisco Cell Culture Facility using deionised water and analytical grade reagents.

**Cell culture**

Bovine pulmonary arterial endothelial cells (BPAECs; ATCC, CCL-209; passages all <8) were cultured, as previously described.\textsuperscript{15} Human lung microvascular endothelial cells (HMVECs; Lonza; CC-064) were cultured either on transwells (Costar 3495, 2×10^5 cells per filter) for 4 days or in 6-well plates until they formed confluent monolayers.

Primary rat alveolar epithelial type II (ATII) cells were isolated and cultured as previously described.\textsuperscript{16}

**Preparation of \textit{P aeruginosa}**

The wild-type, PAK strain of \textit{P aeruginosa} was a kind gift from Dr Stephen Lory at Harvard University, Massachusetts. The PA103 strain of \textit{P aeruginosa} was generously provided by Dr Dana Frank at the Medical College of Wisconsin. The preparation of \textit{P aeruginosa} was performed as previously described.\textsuperscript{15}

**Measurement of transendothelial albumin flux**

Transendothelial albumin flux across BPAECs and HMVECs was measured as previously described.\textsuperscript{15}

**Western blot analysis**

Western blot analysis was performed as described previously.\textsuperscript{17}

**Primers and probes**

Real-time reverse transcription–PCR primers and probes were designed using Primer Express software (PE-Applied Biosystems, Warrington, UK) and purchased from Biosearch Technologies Novato, CA, USA.

**Quantitative real-time RT–PCR**

Quantitative real-time RT–PCR analyses were performed as described previously.\textsuperscript{17}

**RhoA and Rac-1 activity assay in cells**

Rac-1 and RhoA activities were determined using a luminescence-based G-LISA Rac-1 and RhoA activation assay (Cytoskeleton, Denver, Colorado, USA).

**Cell treatment with exogenous PAI-1**

This was performed as described in our previous study.\textsuperscript{18}

**Cell viability assay**

Cell viability was measured by the Alamar Blue assay after exposure to the various experimental conditions.

**RESULTS**

PAI-1 is an essential component of the pulmonary host response during the early phase of \textit{P aeruginosa} pneumonia in mice

We first found that there was a time-dependent increase in plasma and BAL fluid levels of PAI-1 in C57Bl6 mice instilled with \textit{P aeruginosa} (figure 1). We also found that the increase in lung vascular permeability caused by the airspace instillation of two different strains of \textit{P aeruginosa} (PA103 that produces exoU and PAK that does not produce exoU) was significantly attenuated in PAI-1 null mice (figure 2A–D). These results were confirmed by treating the mice with Tiplaxtinin (also called PAI-059), a newly developed pharmacological inhibitor of PAI-1 (figure 2E,F). We next showed that PAI-1 inhibition using PAI-059 (11 μM)
P aeruginosa (PAK) induces PAI-1 expression in pulmonary endothelial and alveolar epithelial cells via a RhoA-dependent mechanism

Exposure of endothelial cells to PAK or transforming growth factor β1 (TGFβ1) resulted in the release of PAI-1 into the cell supernatant (figure 4A). Exposure to PAK also resulted in an increase in PAI-1 gene and protein expression (figure 4B,C). Furthermore, pretreatment of BPAEC monolayers with a ROCK inhibitor (Y-27632, 10 μM) or with a nuclear factor-κB (NF-κB)-dependent kinase (IkB) inhibitor (BMS-545541, 10 μM) significantly decreased PAI-1 protein expression in BPAEC monolayers (figure 4C,D). We also found that inhibition of p38 mitogen-activated protein (MAP) kinase activity with SB98450 (10 μg/ml) significantly decreased PAK-mediated induction of PAI-1 gene and protein expression (figure 5A,B) and protein permeability across BPAEC monolayers induced by P. aeruginosa (figure 5C). Interestingly, inhibition of the p38 MAP kinase decreased PAK-mediated RhoA activation whereas the inhibition of the RhoA-dependent kinase by its inhibitor Y-27632 did not prevent P. aeruginosa-induced p38 MAP kinase activation (figure 5D,E).

Next, we found that PAK-induced p38 MAP kinase activation was largely dependent on activation of Toll-like receptor 4 (TLR4) by this bacterium (figure 5F). Finally, we found that exposure of BPAEC monolayers to human recombinant PAI-1 caused a reversal of the RhoA/Rac-1 activity ratio that resulted in the activation of RhoA and a corresponding inhibition of Rac-1 which could further increase the direct effect of P. aeruginosa on lung vascular permeability (figure 5A,B).

As figure 1 shows, there was a time-dependent increase in PAI-1 BAL fluid levels after airspace instillation of PAK in mice. Therefore, we also examined whether there was an increase in PAI-1 protein expression in alveolar epithelial cell monolayers exposed to P. aeruginosa. Figure 7 shows that PAI-1 protein was significantly increased after PAK exposure (4 h) and that PAK-mediated induction of PAI-1 expression was RhoA dependent (figure 7).

PAI-1 deletion and inhibition inhibits the lung innate immune response and increases mortality during P aeruginosa pneumonia in mice

We next examined the effect of PAI-1 deletion or inhibition on bacterial clearance, mortality and lung innate immune response...
Figure 3  Specific plasminogen activator inhibitor-1 (PAI-1) inhibition attenuates *P aeruginosa*-induced increase in protein permeability and RhoA activity in bovine pulmonary artery and human microvascular lung endothelial cell monolayers. (A–D) Bovine pulmonary artery (BPAEC) and human microvascular (HMVEC) lung endothelial cell monolayers were treated with the wild-type *P aeruginosa* strain PAK (bacterial to bovine cell ratio: 1:2) or its vehicle for 30 min (RhoA activity) or 4 h (permeability measurement). Cell monolayers were pretreated with Tiplaxtinin (PAI-039) (11 μM) or its vehicle for 1 h prior to stimulation with *P aeruginosa* (PAK). All experiments were performed at least in triplicate and repeated three times. Results are shown as mean ± SD; *p<0.05 from controls; #p<0.05 from cell monolayers treated with PAK and PAI-039 vehicle.

Figure 4  *P aeruginosa* causes plasminogen activator inhibitor-1 (PAI-1) gene and protein expression via a RhoA- and nuclear factor-κB (NF-κB)-dependent mechanism in bovine pulmonary artery epithelial cell (BPAEC) monolayers. (A) *P aeruginosa* causes the extracellular release of PAI-1 protein by BPAEC monolayers. BPAEC monolayers were treated with the wild-type *P aeruginosa* strain PAK or its vehicle for 24 h (bacterial to bovine cell ratio: 1:5). Transforming growth factor β1 (TGF-β1) (10 ng/ml) served as a positive control. (B and C) *P aeruginosa* causes PAI-1 gene and protein expression via a RhoA-dependent mechanism in BPAEC monolayers. BPAEC monolayers were treated with the wild-type *P aeruginosa* strain PAK or its vehicle for 4 h (bacterial to bovine cell ratio: 1:2). Cell monolayers were treated with the ROCK inhibitor Y27632 (10 μM) or its vehicle for 1 h prior to stimulation with *P aeruginosa* (PAK). (D) *P aeruginosa* causes PAI-1 protein expression via an NF-κB-dependent mechanism in BPAEC monolayers. BPAEC monolayers were treated with the wild-type *P aeruginosa* strain PAK or its vehicle for 4 h (bacterial to bovine cell ratio: 1:2). Cell monolayers were treated with the NF-κB-dependent kinase (IκB) inhibitor BMS-345541 (10 μM) or its vehicle for 1 h prior to stimulation with *P aeruginosa* (PAK). All experiments were performed at least in triplicate and repeated at least three times. For western blots, a representative blot is shown. Three additional experiments gave comparable results. Results are shown as mean ± SD; *p<0.05 from negative or positive controls; #p<0.05 from cell monolayers treated with PAK and Y27632 or BMS-345541 vehicle.

using our murine model of *P aeruginosa* pneumonia. PAI-1 deletion or inhibition was associated with a significant decrease in lung bacterial clearance (figure 8A,B) and higher mortality (figure 8C). In the next series of experiments, we examined whether the decreased bacterial clearance observed in mice with disrupted PAI-1 signalling was caused by a defect in neutrophil...
mobilization into the lung in response to the airspace instillation of P aeruginosa. We found that PAI-1 null mice or wild-type mice treated with PAI-039 had a decreased neutrophil recruitment into the lung in response to the airspace instillation of P aeruginosa (figure 9A,B). Disruption of PAI-1 signalling was also associated with a lower myeloperoxidase activity in the lungs (figure 9C) and lower BAL fluid levels of KC, a major murine neutrophil chemokine (figure 9D).

**DISCUSSION**

A growing body of literature has highlighted clinical correlations between elevated plasma, BAL or pulmonary oedema fluid levels of PAI-1 and severe disease, as well as adverse clinical outcome in both patients with ALI and with pneumonia caused by P aeruginosa. Decreased airspace fibrinolysis in patients with pneumonia has mainly been attributed to an elevation in PAI-1 activity and precedes the clinical recognition of VAP by several days in critically ill patients. However, it was still unknown whether there is a role for PAI-1 in lung injury induced by bacteria, such as P aeruginosa. Using the combined approach of PAI-1 gene deletion and pharmacological inhibition, we found that the release of PAI-1 in response to the exposure to P aeruginosa is an important contributor to the early alterations in the lung fluid balance caused by P aeruginosa. Moreover, PAI-1...
inhibition also protected against \textit{P} \textit{aeruginosa}-mediated lung cell endothelial leak in vitro, indicating a direct effect of PAI-1 release by \textit{P} \textit{aeruginosa} on the barrier function of lung endothelial cells via a RhoA-dependent mechanism.

The importance of RhoA in mediating the inflammatory response elicited by \textit{P} \textit{aeruginosa} is supported by our previous in vivo and in vitro studies that reported a central role for this small GTPase in the regulation of the endothelial barrier permeability after \textit{P} \textit{aeruginosa} challenge.\textsuperscript{15, 19} There are several pathways that could lead to RhoA activation by \textit{P} \textit{aeruginosa} in pulmonary endothelial cells that include the activation of TLR4 and TLR5 by the bacterial endotoxin and flagellin.\textsuperscript{23, 24} Our results indicate that RhoA activation and PAI-1 expression induced by \textit{P} \textit{aeruginosa} depend in part on a TLR4-mediated phosphorylation of the p58 MAP kinase and activation of RhoA. However, \textit{P} \textit{aeruginosa} may also activate RhoA signalling via the

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\caption{Figure 6: Recombinant plasminogen activator inhibitor-1 (PAI-1) increases RhoA and inhibits Rac-1 activity in bovine pulmonary artery epithelial cell (BPAEC) monolayers. (A and B) BPAEC monolayers were treated with human recombinant PAI-1 (20 \(\mu\)g/ml) or its vehicle for 30 min. All experiments were performed at least in triplicate and repeated at least three times. Results are shown as mean \pm SD; *p<0.05 from controls.}
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\caption{Figure 7: \textit{P} \textit{aeruginosa} causes plasminogen activator inhibitor-1 (PAI-1) protein expression via a RhoA-dependent mechanism in primary cultures of alveolar epithelial type II cell monolayers. Rat alveolar epithelial type II cell monolayers cultured on transwells with an air–liquid interface were treated with the wild-type \textit{P} \textit{aeruginosa} strain PAK or its vehicle for 3 h (bacterial to rat cell ratio: 1:2). Cell monolayers were treated with the ROCK inhibitor Y27632 (10 \(\mu\)M) or its vehicle for 1 h prior to stimulation with \textit{P} \textit{aeruginosa} (PAK). A representative western blot is shown. Three additional experiments gave comparable results. Results are shown as mean \pm SD; *p<0.05 from controls; #p<0.05 from cell monolayers treated with PAK and Y27632 vehicle.}
\end{figure}
reported an important role for TGFβ1, a major inducer of PAI-1, in mediating the breakdown of the alveolar epithelial barrier associated with ALI. TGFβ1 also mediates the increase in protein permeability and inhibition of baseline and cAMP-dependent vectorial fluid transport across the alveolar epithelial barrier in experimental rodent models of ALI. In addition, P. aeruginosa increases protein permeability across rat alveolar epithelial type II cell monolayers, an effect that was inhibited by a specific inhibitor of RhoA or a soluble type II receptor for TGFβ1. Interestingly, one of the major mechanisms mediating TGFβ1 activation in the distal lung epithelium is the activation of RhoA by interleukin 1β or thrombin agonists that results in an αvβ6-integrin-mediated activation of TGFβ1 on alveolar epithelial cells, suggesting that PAI-1 could activate TGFβ1 signalling via a RhoA-dependent mechanism. These results indicate that P. aeruginosa causes the expression of PAI-1 protein by the distal lung epithelium and that the release of PAI-1 in the distal airspace may contribute to the breakdown of the alveolar epithelial barrier associated with P. aeruginosa pneumonia.

Conflicting results have been reported concerning the overall role of PAI-1 in various experimental models of pneumonia. For example, Renckens et al have reported that PAI-1 is protective during severe Gram-negative pneumonia caused by Klebsiella pneumoniae, but did not influence the outcome of Gram-positive pneumonia caused by Streptococcus pneumoniae in mice. We found that PAI-1 plays an important role in bacterial clearance from the lung and survival in our experimental model of P. aeruginosa pneumonia because deletion or inhibition of this protein caused a decreased neutrophil recruitment into the lung in response to the airspace instillation of P. aeruginosa. Our results are in accordance with previous studies that showed that PAI-1 regulates neutrophil recruitment into several organs, such as the lung and kidney. In addition to its role in recruiting neutrophils into the lung, PAI-1 expression on the non-apoptotic macrophages protects these immune cells against effecrocytosis (phagocytosis of viable cells) by alveolar macrophages. These results indicate that PAI-1 is required for the activation of the innate immune response necessary for the eradication of P. aeruginosa from the distal airspaces of the lung.

In summary, we have demonstrated a dual role for PAI-1 during the course of P. aeruginosa pneumonia in mice. Despite an early protective effect of the function of the alveolar capillary barrier, the lack of PAI-1 activity was later associated with the inability to clear the bacteria from the airspace and increased...
mortality. This apparent dichotomy may in fact reflect a synergistic host response to bacterial lung infection that has to be tightly controlled. Indeed, an exaggerated release of PAI-1 in the extracellular space may lead to the development of severe pulmonary edema that would overwhelm PAI-1 effects on the lung innate immune response and explain the clinical correlation between high BAL fluid and plasma levels of PAI-1 and poor outcome in patients with \textit{P aeruginosa} pneumonia.\textsuperscript{10} Additional studies that will include multiple time points and several strains of \textit{P aeruginosa} will be needed to answer this critical question. Despite this limitation, the present study demonstrates that PAI-1 controls the development of the early lung inflammation that is required for the activation of the innate immune response necessary for the eradication of \textit{P aeruginosa} from the distal airspace of the lung, suggesting that therapeutic approaches that would inhibit the early inflammation may be deleterious for the host. Indeed, patients with high \textit{P aeruginosa} burden in their lungs, but with a weak inflammatory response, have an increased mortality from \textit{P aeruginosa} pneumonia.\textsuperscript{3, 5}

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**Competing interests** None.

**Provenance and peer review** Not commissioned; externally peer reviewed.

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**REFERENCES**


Combined use of transoesophageal and transbronchial ultrasonography may lead to fewer unnecessary thoracotomies while staging NSCLC

This study investigated the use of endosonography versus surgical staging in non-small cell lung cancer. Patients in the endosonography arm underwent transbronchial and transoesophageal ultrasonography to detect mediastinal involvement followed by surgical staging if no nodal involvement was found.

Two hundred and forty-one patients were randomised for surgical staging (118) or endosonography (123). Sixty-five patients in the endosonography group also underwent surgical staging. Nodal metastasis was found in 41 patients (35%) by surgical staging compared with 56 patients (46%) by endosonography alone and 62 patients (50%) by endosonography followed by surgical staging. Thoracotomy was unnecessary in 21 patients (18%) in the mediastinoscopy group compared with 9 patients (7%) in the endosonography group.

The use of combined endosonography and surgical staging resulted in an improvement in the detection of nodal metastasis and a reduction in unnecessary thoracotomies compared with surgical staging alone in patients with suspected non-small cell lung cancer. However, several nodes were out of reach of endosonography, and the technique is not available in all centres. Further research is needed, and the question remains as to whether all routinely negative endosonography patients should have mediastinoscopy or whether this approach is meant for a particular subgroup.


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