Both Circulating and Clot-Bound Plasminogen Activator Inhibitor–1 Inhibit Endogenous Fibrinolysis in the Rat

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The effects of both clot-bound and circulating plasminogen activator inhibitor–1 (PAI-1) on endogenous fibrinolysis were investigated in a rat model of pulmonary embolism. Iodine-125 fibrinogen–labeled blood-clot homogenates were delivered through the left jugular vein to the lung microvasculature, and the subsequent extent of the clot lysis was monitored by measuring the release of 125I–fibrin degradation products (FDPs) into the blood. Clots that had incorporated activated PAI-1 ex vivo were subsequently protected from dissolution in vivo in a dose-responsive manner (half-maximal concentration \( IC_{50} = 4.3 \mu g/ml \)). PAI-1–containing clots also resisted lysis, as measured by the release of the specific FDP D-dimer. Plasma levels of plasminogen activator (PA) and PAI activity were unaltered by administration of PAI-1–containing clots, and the clot-protective effects of clot-bound PAI-1 were reversed by exogenous tissue-type plasminogen activator administration. Clot lysis was also inhibited in a dose-responsive manner (\( IC_{50} = 58 \mu g/kg \)) by intravenous bolus delivery of activated PAI-1 to the circulation. The clot-protective effects of circulating PAI-1 were correlated with dose-dependent increases in plasma PAI-1 antigen and activity levels and decreases in plasma PA levels (\( IC_{50} = 37 \mu g/ml \)). There was no evidence of any accumulation of circulating PAI-1 in the lungs. Latent PAI-1, whether delivered with or delivered after the clot homogenates, did not affect the clot-lytic process. Activated and latent PAI-1 was cleared from the circulation in a monophasic manner, with a half-life of approximately 32 and 7 minutes, respectively. The results indicate that both clot-bound and circulating PAI-1 are potent inhibitors of fibrinolysis in vivo. Clot-bound PAI-1 may inhibit PAs in the immediate vicinity of the clots, whereas circulating PAI-1 may act systemically by controlling overall levels of PAs present in the blood. (Arteriosclerosis and Thrombosis 1991;11:1276–1286)

The fibrinolytic system maintains blood vessel patency by clearing the vasculature of fibrin. The importance of this process to normal hemostasis is underscored by the links between an elevated fibrinolytic potential to bleeding and a depressed fibrinolytic system to thrombosis and possibly atherosclerosis. Plasminogen activator inhibitor–1 (PAI-1) may play a key role in regulating fibrinolysis. PAI-1 is a member of the SERPIN class of proteinase inhibitors and is the fastest-acting known inhibitor of the plasminogen activators, tissue-type plasminogen activator (t-PA) and urokinase (UK). t-PA and UK initiate fibrinolysis by converting plasminogen to the fibrin-degrading proteinase, plasmin. PAI-1 circulates in plasma, and PAI-1 levels are inversely related to the levels of plasminogen activator(s) (PAs) present. Two forms of PAI-1 have been identified: an active form and an inactive latent form. Latent PAI-1 can be activated in vitro by treatment with strong denaturants such as sodium dodecyl sulfate and guanidine HCl. Whether activation occurs in vivo is unknown. Clinical studies have associated elevations in plasma PAI-1 levels with an increased risk of thrombosis, whereas decreases in plasma PAI-1 levels may lead to bleeding episodes. Results obtained in experimental animal models suggest that increases in the levels of circulating PAI-1 or inhibition of PAI-1 with blocking monoclonal anti–PAI-1 antibodies are prothrombotic and antithrombotic, respectively. Thus, elevations in the levels of circulating PAI-1 may lead to suppression of the systemic fibrinolytic pathway, with a concomitant tendency to thrombose. Like other members of the fibrinolytic pathway, PAI-1 may participate in the regulation of localized fibrinolytic events. Endothelial cells and vascular
smooth muscle cells \cite{24,25} synthesize and release PAI-1, especially after stimulation with inflammatory mediators and growth factors, including endotoxin, transforming growth factor-\(\beta\), tumor necrosis factor, and platelet-derived growth factor. Platelets store large amounts of PAI-1, which is released on platelet activation.\cite{6,7} PAI-1 also binds to fibrin\cite{26} and vitronectin,\cite{27} and the bound PAI-1 is capable of inhibiting t-PA and UK. Recent studies indicate that human thrombi\cite{28} as well as experimentally induced porcine thrombi\cite{29} contain greatly elevated levels of PAI-1 relative to the levels in the normal circulation. Thus, large amounts of platelet-derived PAI-1 or PAI-1 released from the vascular wall could accumulate at sites of vascular injury or forming thrombi by binding to fibrin or vitronectin and thereby generate an antifibrinolytic microenvironment.

Studies concerning the in vivo behavior and role of PAI-1 in the fibrinolytic system are limited. Knabb et al\cite{10} demonstrated that high levels of circulating PAI-1 inhibited clot dissolution in a rabbit model, and we have recently demonstrated that whole-blood clot homogenates, which had incorporated PAI-1 ex vivo, were protected from lysis in a canine model of pulmonary embolism.\cite{31} Given the potential importance of PAI-1 to the generation of a prothrombotic state, we systematically examined the effects of both clot-bound and circulating PAI-1 on the fibrinolytic system in a rat model of pulmonary embolism.

**Methods**

**Materials**

Two-chain t-PA (2ct-PA; 920 IU/\(\mu\)g) and Immubind PAI-1 enzyme-linked immunosorbent assay (ELISA) kits were obtained from American Diagnostica, Greenwich, Conn. Human fibrinogen was purchased from Calbiochem, La Jolla, Calif., and predominantly single-chain t-PA (Activase) was obtained from Genentech, South San Francisco, Calif. Guanidine HCl was obtained from Schwarz/Mann, Cleveland, Ohio. Iodine-125-labeled Bolton-Hunter reagent and 125\(^{I}\)-bovine serum albumin (BSA; 1 mCi/mg) were from NEN, Boston, Mass., and ICN Biomedicals, Costa Mesa, Calif., respectively. Fibrinogen was iodinated by the Iodogen method\cite{32} and possessed a specific radioactivity of 1 mCi/mg.

**Plasminogen Activator Inhibitor–1**

A nonglycosylated recombinant form of human PAI-1 (\(M_w=43,000\)) was expressed intracellularly in *Saccharomyces cerevisiae* and purified to homogeneity.\cite{33} The purified PAI-1 was in a latent essentially inactive form as described by others\cite{10} and was activated by treatment with guanidine HCl.\cite{31,34} The guanidine HCl was subsequently removed by gel filtration in 0.05 M tris(hydroxymethyl)aminomethane HCl, 0.1 M NaCl, 0.01% Tween-80 (pH 7.4) (TNT buffer) at 4°C. The inhibitory activity of PAI-1 was determined by adding PAI-1 to a known amount of 2ct-PA and measuring the residual t-PA activity in a coupled amidolytic assay, which measures the conversion of plasminogen to plasmin by t-PA.\cite{28} One arbitrary unit (AU) is defined as the amount of PAI-1 required to inhibit one IU t-PA. Activated PAI-1 was approximately 35% active and possessed a specific activity of approximately 509 AU/\(\mu\)g. Latent PAI-1 had a specific activity of less than 5 AU/\(\mu\)g.

**Measurement of Endogenous Fibrinolysis In Vivo**

Male Sprague-Dawley rats, 270–400 g, were anesthetized with sodium pentobarbital (32 mg/kg body wt i.v.). The left jugular vein was cannulated for clot administration, and the right carotid artery was cannulated for blood withdrawal and a maintenance infusion of sodium pentobarbital (4 mg/hr). One milliliter blood was drawn and mixed with 1 \(\mu\)Ci 125\(^{I}\)-fibrinogen and either 300 \(\mu\)l vehicle or PAI-1 (1.2–30 \(\mu\)g). Vehicle consisted of TNT buffer containing 120 mM guanidine HCl to control for the residual guanidine HCl remaining after PAI-1 activation. After the blood was allowed to clot for 1 hour at 37°C, the clot was homogenized to a fine suspension in a glass–glass homogenizer (Kontes). The homogenate was centrifuged at 5,000g, washed three times in phosphate-buffered saline (PBS), and finally resuspended in 1 ml PBS before use. The extent of 125\(^{I}\)-fibrinogen incorporation into the washed clot suspension ranged from 60% to 90%. At time zero, the homogenate (0.5 ml/kg body wt) was injected into the jugular vein of the anesthetized rats. Blood samples (0.2 ml) were drawn at intervals for determination of 125\(^{I}\)-fibrin degradation products (FDPs). Total blood radioactivity was calculated with the assumption that the blood volume per weight ratio equaled 10%. In some cases the animals were killed by an intravenous injection of 1 ml KCl, and the lungs or other organs were obtained for counting. In other experiments t-PA (Activase) was administered 1 minute after clot delivery at 1 mg/kg body wt as a 10% loading dose, and the remainder was infused during the subsequent 60-minute period (0.026 ml/min). Care and handling of experimental animals conformed to the standards established by the Merck Sharp and Dohme Research Laboratories Institutional Animal Care and Use Committee, as recommended in National Institute of Health publication No. 86-23.

**Plasminogen Activator Inhibitor–1 Binding Studies**

PAI-1 was radiolabeled with 125\(^{I}\)-Bolton-Hunter reagent to a specific activity of approximately 4\times10^4 cpm/\(\mu\)g. After guanidine HCl activation, 125\(^{I}\)-PAI-1 retains its inhibitory activity against t-PA by formation of 1:1 molar sodium dodecyl sulfate stable complexes (C.F. Reilly, unpublished observations). Binding studies were initiated by mixing duplicate samples of rat blood (1 ml) with activated or latent 125\(^{I}\)-PAI-1 (2 ng) and increasing amounts of unlabeled activated PAI-1 (1.2–30 \(\mu\)g/ml). BSA binding was determined by adding 0.65 \(\mu\)Ci 125\(^{I}\)-BSA to the rat blood instead of PAI-1. After a 1-hour incubation at 37°C, the clots were homogenized and washed as described above, and the radioactivity of each clot homogenate was...
Antigen Levels in Rat Plasma

Determination of Plasminogen Activator Inhibitor-1

were linear between 10 and 200 ng/ml. Similar results within the middle range of the standard curves, which had been prepared in the absence of PAI-1, were delivered to the rat lungs. The extent of PAI-1 delivered to the lungs was calculated from the amount of $^{125}$I-PAI-1 present in the lungs at 1 and 60 minutes after delivery.

Determination of D-Dimer Levels

were obtained when the standard curves were generated in plasma pooled from normal rats.

Other Procedures

PAI-1 activity levels in citrated plasma were determined as described by Chmielewska and Wiman. The PA activity of freshly drawn acidified plasma was measured as described in the directions of the Kabivitrum COA-SET t-PA kit (KabiVitrum, Stockholm, Sweden). Results are presented as mean±SEM unless stated otherwise. Statistical significance ($p<0.05$) of differences among treatments was determined by a two-way analysis of variance of repeated measures and a one-sided Dunnett's multiple-comparison test or Student's $t$ test.

Results

Plasminogen Activator Inhibitor-1 Binds to Rat Whole-Blood Clot Homogenates

To establish whether PAI-1 binds to clots prepared from rat blood, increasing amounts of PAI-1 and trace amounts of $^{125}$I-PAI-1 were added to freshly drawn rat whole blood. After the blood was allowed to clot spontaneously for 1 hour, the clot was homogenized to a fine suspension and washed thoroughly to remove any unbound PAI-1, and the radioactivity of the final clot suspension was determined. After addition of activated or latent PAI-1 at 1.2, 6, and 30 μg/ml blood, 0.12±0.02, 0.67±0.8, and 3.55±0.24 μg/ml activated PAI-1 (four determinations) and 0.08±0.01, 0.28±0.2, and 1.57±0.24 μg/ml latent PAI-1, respectively (mean±range of two determinations), became tightly associated with the final clot homogenates. Thus, approximately 11% of the activated and 5.5% of the latent PAI-1 bound to the clot homogenates at each concentration examined. Because the association of PAI-1 with the clots could represent nonspecific trapping within the fibrin meshwork, $^{125}$I-BSA was added to rat blood, and the amount bound was determined. After clotting, 1.9±0.2% (three determinations) of the total BSA was found to be associated with the washed homogenates. Thus, most of the binding of activated and latent PAI-1 to the clots does not arise from nonspecific trapping within the clots.

Delivery of Plasminogen Activator Inhibitor-1–Enriched Clots to the Rat Lung

Homogenates containing activated $^{125}$I-PAI-1 were prepared as described above and delivered to rats through the left jugular vein. Clot suspensions delivered in this manner lodge in the microvasculature of the lung (see below). The animals were killed 1 or 60 minutes after clot delivery, and the amount of PAI-1 present in the lungs was established by measuring the radioactivity. Comparison of the amount of PAI-1 delivered to the rats relative to the amount of PAI-1 present in the lungs (Table 1) indicates that 74–82% of the PAI-1 was retained in the lung tissue 1 minute after administration. At 60 minutes, 59–67% of the PAI-1 was present in the lungs. These results indicate that most of the PAI-1, which was incorporated into the clots ex vivo, accumulates in the lungs. Furthermore, a considerable amount of PAI-1 remains in the lungs even after 60 minutes in vivo.
was low along the route of administration and in continued to increase in a linear manner for 60 minutes (Figure 1A). In contrast, the activated PAI-1-treated appeared in the blood within 10 minutes and continued to lodge in the microvasculature of the lung. Thus, the 125I-fibrin(ogen)-labeled clot suspensions were dispersed throughout both lungs and other tissues, including blood, heart, kidney, and liver. Therefore, the 125I-fibrin(ogen)-labeled clot suspensions lodge in the microvasculature of the lung.

After delivery of vehicle-treated clots, 125I-FDPs appeared in the blood within 10 minutes and continued to increase in a linear manner for 60 minutes (Figure 1A). In contrast, the activated PAI-1–treated clots resisted lysis in a dose-responsive manner (p<0.0001) (Figure 1A). At initial PAI-1 levels of 6 and 30 μg/ml, 125I-FDP levels were significantly less than in the vehicle-treated clots (p<0.0001). The lowest level of PAI-1 employed (1.2 μg/ml) did not significantly affect blood levels of 125I-FDPs relative to controls. At 60 minutes, the 6 and 30 μg/ml levels of PAI-1 had reduced blood radioactivity by 60% and 85%, respectively, as judged by computing the areas under the curves in Figure 1A. The half-maximal effective dose (IC50) of PAI-1 at 60 minutes equaled 4.3 μg/ml. The inhibitory effects of PAI-1 on clot lysis were temporal, as 125I-FDP blood levels increased slowly with time, even at the highest dose of PAI-1 used (30 μg/ml, Figure 1A). Blood levels of 125I-FDPs were essentially identical in animals that received clots formed in the presence of vehicle or a high dose of unactivated latent PAI-1 (30 μg/ml) (Figure 1B).

The amount of 125I-fibrin(ogen) remaining in the lungs was measured 60 minutes after delivery of either vehicle-treated clots or clots prepared in the presence of activated PAI-1 (30 μg/ml). Relative to the amount of 125I-fibrin(ogen) delivered (approximately 250,000 cpm/rat), significantly more radioactivity remained in the lungs of rats that had received the PAI-1–treated clots (vehicle, 51.4±2.2%, n=6; 30 μg/ml PAI-1, 77.8±3.4%, n=6; p<0.0001 by Student’s t test).

The effect of PAI-1 on clot dissolution was also monitored by measuring the release of D-dimer from clots formed in the presence of vehicle or activated PAI-1 (30 μg/ml). D-Dimer is a specific FDP that is released from fibrin by plasmin. Antibodies are available that recognize human D-dimer; therefore, rat clot homogenates containing a small amount of hu-

### Table 1. Plasminogen Activator Inhibitor-1 Remaining in the Lungs at 1 and 60 Minutes After Clot Delivery

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Initial PAI-1 (μg/ml blood)</th>
<th>PAI-1 bound (ng/ml blood)</th>
<th>PAI-1 delivered (ng/kg)</th>
<th>PAI-1 remaining (ng/kg)</th>
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<td>98</td>
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<tr>
<td>30</td>
<td>3,697</td>
<td>1,848</td>
<td>1,231±90</td>
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</table>

Activated iodine-125-labeled plasminogen activator inhibitor-1 (PAI-1) (6×10⁵ cpm) was added to freshly drawn rat whole blood with the indicated amount of unlabeled activated PAI-1. One hour later clots were homogenized and washed, and the amount of PAI-1 that bound to the clot homogenates was determined as described in Methods. Clot homogenates containing a known amount of PAI-1 were delivered (0.5 ml/kg) to the lungs (two rats at each dose). The amount of PAI-1 remaining (mean±range) in the lungs at 1 or 60 minutes after clot delivery was calculated from the total radioactivity present in the excised lungs.

**FIGURE 1.** Line plots showing that clot-bound activated plasminogen activator inhibitor-1 (PAI-1) but not latent PAI-1 inhibits iodine-125–labeled fibrin degradation product (FDP) release from experimental pulmonary emboli. 125I-fibrin(ogen) containing clot homogenates, prepared in the presence of vehicle, activated PAI-1, or latent PAI-1, were delivered through the left jugular vein to the lungs at time zero. At indicated times (min) blood samples were withdrawn, and levels of 125I-FDPs were determined. Data are expressed as the percentage of administered radioactivity that was present in the total blood volume at each time point and assumes a blood volume to weight ratio of 10%. PAI-1 concentrations are per milliliter of blood before clot homogenization. Panel A: Activated PAI-1: ○, Vehicle, n=8; ■, 1.2 μg/ml PAI-1, n=7; ▲, 6 μg/ml PAI-1, n=6; ●, 30 μg/ml PAI-1, n=7. Panel B: Latent PAI-1: ○, Vehicle, n=8; ▲, 30 μg/ml latent PAI-1, n=7. Vehicle data in panel B were from the experiment described in panel A.
FIGURE 2. Line plot showing plasminogen activator inhibitor-1 (PAI-1) inhibition of D-dimer release (ng/ml). Clot homogenates prepared in the presence of vehicle or activated PAI-1 (30 µg/ml) and containing small amounts of human fibrinogen were delivered to the lungs at time zero. Blood samples were withdrawn at indicated times (min), and the amount of D-dimer present in plasma was determined by use of an immunoassay that measures human D-dimer. Rat plasma did not interfere with the assay. ●, Vehicle, n=3; ■, PAI-1, n=4.

Activated Plasminogen Activator Inhibitor-1 in the Circulation Inhibits Clot Dissolution In Vivo

The above experiments addressed the role of PAI-1, which was prebound to the clots, on the subsequent fate of the clots. We also determined whether PAI-1 systemically administered to the circulation inhibits clot lysis. Activated PAI-1 was delivered by bolus intravenous injection 1 minute after 125I-fibrin(ogen)-labeled clots were directed to the lungs. Under these conditions PAI-1 significantly reduced 125I-FDP blood levels in a dose-dependent manner (p<0.0001) (Figure 4A). Relative to vehicle, PAI-1 at 20, 100, and 300 µg/kg reduced blood radioactivity levels by 25%, 62%, and 74%, respectively, as judged by computation of the area under the curve at the 60-minute time point. The IC50 of activated PAI-1 was 58 µg/kg. Activation of PAI-1 was critical for its clot-protective effects because blood levels of 125I-FDPs were nearly identical at all times after administration of vehicle or latent PAI-1 (300 µg/kg) (Figure 4B).

Activated Plasminogen Activator Inhibitor-1 in the Circulation Inhibits the Systemic Fibrinolytic System

To elucidate the mechanism underlying the clot-protective effects of activated PAI-1 shown in Figure 4A, plasma levels of PAI-1 antigen, PAI-1 activity,
and PA activity were determined after bolus administration of activated PAI-1 to rats bearing lung clots. PAI-1 antigen levels increased immediately after bolus administration of 20, 100, and 300 µg/kg activated PAI-1 (Figure 5). The initial levels of PAI-1 were similar to the values predicted from the administered dose, assuming a 10% blood volume to weight ratio and a uniform distribution in the circulation. PAI-1 antigen cleared from the circulation in a monophasic manner, with a half-life (t1/2) of 27.6 ± 0.9 minutes (mean of 20, 100, and 300 µg/kg values).

PAI-1 activity in plasma increased 10-, 43-, and 114-fold immediately after delivery of activated PAI-1 at 20, 100, and 300 µg/kg, respectively, relative to the basal levels present in rat plasma (13.3 ± 0.7 AU/ml, n = 6) (Figure 6). The initial levels of PAI-1 activity at the three different doses were close to those predicted from the antigen levels measured in Figure 5. PAI-1 activity subsequently cleared from the circulation in a monophasic manner, with a t1/2 of 35.3 ± 2.4 minutes (mean of 20, 100, and 300 µg/kg values). Essentially similar pharmacokinetic behavior has been observed in rabbits, where activated PAI-1 activity and antigen cleared from the circulation through a predominant β phase, with a t1/2 of approximately 30 minutes.34

Within 10 minutes of activated PAI-1 bolus administration, decreases in the levels of PA activity in the circulation were apparent (Figure 7). The reductions in PA levels were sustained for 60 minutes and were dependent on the initial dose of PAI-1. Administration of PAI-1 at 20 and 100 µg/kg resulted in a 35.7 ± 0.9% and a 71 ± 2.5% inhibition of PA activity in plasma, respectively (mean inhibition at 10, 30, and 60 minutes). Administration of PAI-1 at the highest dose (300 µg/kg) did not result in further PA inhibition (69.7 ± 5.3%) relative to the 100 µg/kg dose. Thus, one of the components responsible for PA activity in rat plasma may resist inhibition by PAI-1. The IC50 of activated PAI-1 equaled 37 µg/kg.

The presence of clot homogenates in the lungs did not influence the pharmacokinetic behavior of activated PAI-1. Nearly identical clearance profiles were measured for PAI-1 antigen (Figure 8A), PAI-1 activity (Figure 8B), and inhibition of plasma PA.
Figure 6. Line plot of plasma levels (AU/ml) of plasminogen activator inhibitor-1 (PAI-1) activity after bolus administration. Activated PAI-1 was delivered by bolus intravenous administration to rats bearing clots. At indicated times (min) plasma samples were obtained, and the levels of PAI-1 activity were determined. ○, 20 µg/kg PAI-1; ●, 100 µg/kg PAI-1; ▲, 300 µg/kg PAI-1. Results are mean±range from two experiments. Basal levels of PAI-1 activity present in normal rat plasma equalled 13.3±1.6 AU/ml (n=6). AU, arbitrary unit.

Figure 7. Line plot of plasma levels (%) of plasminogen activator (PA) activity after bolus administration of plasminogen activator inhibitor-1 (PAI-1). Activated PAI-1 was delivered by bolus intravenous administration to rats bearing clots. At indicated times acidified plasma samples were obtained, and the levels of PA activity were determined. ○, 20 µg/kg PAI-1; ●, 100 µg/kg PAI-1; ▲, 300 µg/kg PAI-1. Results are mean±range from two experiments. Basal levels of PA activity before PAI-1 delivery equalled 4.7±0.4 IU/ml (n=6).

Activating plasminogen activator inhibitor-I in the circulation does not bind to the clot homogenates in vivo

To determine whether activated PAI-1 delivered to the circulation binds to clots already present in the lungs, 125I-PAI-1 (2 ng) was added to unlabeled PAI-1 (100 µg/kg), and the mixture was administered to the systemic circulation 1 minute after clot homogenates were directed to the lungs. PAI-1 was also administered to control animals without clots. Sixty minutes later, the amount of radioactivity in the lungs was measured. Relative to the total radioactivity administered, there was slightly more radioactivity present in the lungs of the rats that bore clots (0.81±0.12%, n=5) than in the lungs without clots (0.60±0.03%, n=5). However, the values were not significantly different (p=0.07, one-sided Student’s t test).

Discussion

The effects of both clot-bound and circulating PAI-1 on fibrinolysis have been evaluated in a rat model of pulmonary embolism. The results indicate that elevated levels of PAI-1 in the circulation can...
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PAI-1 Inhibition of Fibrinolysis In Vivo

FIGURE 8. Line plots showing that plasminogen activator inhibitor–1 (PAI-1) exhibits similar clearance patterns and suppresses plasma plasminogen activator (PA) activity to a similar extent in rats with and without clots. After bolus administration of activated PAI-1 (100 μg/kg) plasma samples were obtained and the levels of PAI-1 antigen (ng/ml) (panel A), PAI-1 activity (AU/ml) (panel B) and PA activity (%) (panel C) were determined in rats without clots (——) and in rats with clots in the lungs (—). Results are mean±range from two experiments. Data shown for the rats with clots were obtained from experiments described in Figures 5, 6, and 7 for activated PAI-1 at the 100 μg/kg dose. Basal levels of PAI-1 and PA activity in rats without clots equalled 11.4±1.9 AU/ml and 3.5±0.6 IU/ml, respectively (mean±range, n=2). AU, arbitrary units.

directly suppress the systemic fibrinolytic process. These findings provide direct experimental evidence supporting the idea that the net fibrinolytic potential of the circulation is regulated by the balance between PAI-1 and the PAs present. Moreover, the data confirm and extend our previous results that clot-bound PAI-1 inhibits clot dissolution in vivo31 and fully support the notion that the localization of PAI-1 within a thrombus provides an important thrombus-stabilizing effect.

We first established that PAI-1 binds to blood clots and subsequently protects those same clots from lysis in vivo, as has been previously demonstrated in a canine model.31 When increasing amounts of activated PAI-1 were added to rat whole blood, the concentration of PAI-1 that bound to the final clot suspension rose proportionally. Activation of PAI-1 apparently enhances its binding capability because greater than twofold more activated PAI-1 than latent PAI-1 bound to the clots at every concentration examined. PAI-1 may bind to the clots through an association with the fibrin component because activated PAI-1 and to a lesser extent latent PAI-1 bind to fibrin in vitro.26 The ability of PAI-1 to bind to the clots does not appear to be directly related to its ability to inhibit t-PA, however, as more latent PAI-1 bound to the clots (5.5%) than would be expected from its t-PA-inhibitory activity (<0.5% active). Wagner et al26 reached the same conclusion after studying PAI-1 binding to fibrin. As suggested by the extent of PAI-1 found in the lung tissue after delivery of the PAI-1–containing clots, the inhibitor is delivered with the clots to the lungs and remains tightly bound to the clots even after 60 minutes in vivo. Thus, the effects of clot-bound PAI-1 on clot

FIGURE 9. Line plots showing pharmacokinetic behavior and effect on plasma plasminogen activator (PA) activity of latent plasminogen activator inhibitor–1 (PAI-1). After bolus administration of latent PAI-1 (300 μg/kg) plasma samples were obtained, and the levels of PAI-1 antigen (ng/ml) (panel A), PAI-1 activity (AU/ml) (panel B), and PA activity (IU/ml) (panel C) were determined in rats bearing clots in the lungs. Results are mean±range from two experiments. Basal levels of PAI-1 and PA activity equaled 16.2±1.7 AU/ml and 4.4±1.0 IU/ml, respectively (mean±range, n=2). AU, arbitrary units.

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lysis are due to the PAI-1 that was delivered with the clots to the lungs.

Activated PAI-1, delivered prebound to the clot homogenates, subsequently protected those clots from the endogenous fibrinolytic system of the rat lung in a dose-responsive manner. Blood levels of $^{125}$I-FDPs were significantly lower in rats with PAI-1–treated clots than in rats that had received vehicle-treated clots. Moreover, the levels of $^{125}$I-fibrinogen remaining in the lungs with PAI-1–treated clots were significantly higher than in controls. This latter observation eliminates the possibility that the reductions in blood radioactivity resulted from alterations in the rate of FDP clearance from the circulation. Additional experiments indicated that the release of the defined FDP, d-dimer, from rats bearing PAI-1–treated clots was significantly reduced. Together, these data indicate that the observed reductions in circulating $^{125}$I-FDPs are related directly to PAI-1 inhibition of the rate of clot dissolution in the lung microvasculature. Because the delivery of exogenous t-PA to the rats accelerated the rate of clot lysis and completely reversed the clot-protective effects of the clot-bound PAI-1, PAI-1 most likely inhibited clot dissolution by directly inactivating the endogenous PAs responsible for initiation of the fibrinolytic process. In contrast to activated PAI-1, clot-bound latent PAI-1 did not affect clot dissolution. Although this may be related to the relatively weaker binding of latent PAI-1 to the clots, other data (see below) indicate that fibrinolysis was also unimpaired in the presence of latent PAI-1 in the circulation.

Clot lysis in the absence of PAI-1 or its inhibition in the presence of clot-bound PAI-1 occurred without changing the normal levels of PAI or PA activity in the general circulation. Thus, the clot-protective effects of PAI-1 can be ascribed to the PAI-1 that was delivered with the clots and not to the increases in plasma PAI-1 that can occur after surgery or as an acute-phase type of reaction. Because the introduction of clot-bound PAI-1 did not lead to a generalized inhibition of PAs in the systemic circulation, clot-bound PAI-1 probably inhibits PAs locally in the microenvironment of the clot homogenates that were lodged in the lung tissue.

PAI-1 circulates in human plasma at levels of approximately 10 ng/mL. Thus, the initial levels of PAI-1 added to the rat blood ex vivo and required for clot protection (IC$_{50}$=4.3 μg/mL, Figure 1A) appear to be well above what is considered the normal physiological levels of PAI-1. This discrepancy could arise from the use of human PAI-1 to inhibit the rat fibrinolytic system or from the presence of reversible PA inhibitors in plasma that interfere with PAI-1–PA binding. In addition, the PAI-1 employed in these studies is only partially (35%) active after guanidine HCl activation. Because only 11% of the added PAI-1 actually bound to the final blood clot homogenates, the concentration of PAI-1 required to protect clots in vivo may be 473 ng/mL blood clot. The normal complement of platelets in 1 ml blood can release more than 200 ng PAI-1 on activation.

Next we asked if circulating PAI-1 inhibited endogenous fibrinolysis in this model. Bolus intravenous administration of activated PAI-1 led to a dose-dependent inhibition of clot lysis, as measured by suppression of the $^{125}$I-FDP levels in blood. Knabb et al. have demonstrated that continuous intravenous infusion of PAI-1 also suppresses clot lysis in a rabbit model. In our experience, inhibition of clot dissolution was correlated with dose-dependent increases in the plasma levels of PAI-1 activity and antigen after PAI-1 administration. The increases in PAI-1 antigen and activity levels were accompanied by dose-dependent decreases in the levels of PA activity in plasma and probably reflect direct inactivation of PAs by PAI-1 in the circulation. The relatively large amounts of circulating PAI-1 required for inhibition of plasma PA activity as well as suppression of clot lysis may be due to the same factors noted above for clot-bound PAI-1. Importantly, comparison of the effects of activated PAI-1 on clot lysis and plasma PA activity (Table 2) yields similar inhibition values at each dose. These results are reflected by the respective IC$_{50}$ values for inhibition of clot lysis (58 μg/kg) and inhibition of plasma PA activity (37 μg/kg). These data suggest that the increased stability of clots in the presence of circulating PAI-1 stems from PAI-1–mediated inhibition of PAs in the circulation and the resultant diminution in fibrinolytic potential. This view is supported by the finding that only minimal amounts of circulating PAI-1 could have been associated with the clots in vivo. Identical PAI-1 pharmacokinetic profiles were observed in the presence and absence of clots in the lungs; moreover, little if any of a radiolabeled PAI-1 preparation delivered to the circulation was associated specifically with the clots present in the lungs. The lack of binding relative to that observed when blood is allowed to clot ex vivo may arise from the cross-linked nature of the clots, which would physically limit the access of PAI-1. We infer from these data that the effects of circulating PAI-1 on fibrino-
PAI-1 accumulation at localized sites, due to pro-lon-ge
d platelet activation or PA-I release from an activated vascular wall,23,25 is potentially prothrom-
botic. Moreover, clinical detection of an associated prothrombotic state could be impaired because the plasma levels of PAI-1 and PA activity remained unchanged after the introduction of PAI-1–enriched clots to the lungs.

PAI-1 also appears to regulate the systemic fibrinolytic pathway. Under normal circumstances, excessive activation or suppression of the fibrinolytic system may be prevented by the approximately equivalent balance existing between the levels of PAs and PA-I present in the circulation.8–9 As our data indicate, however, increases in plasma PA-I levels would lead directly to reductions in the levels of circulating PAs. Fewer PAs would be available for recruitment to the site of a thrombus, and thus, the overall fibrinolytic system would be inhibited. These latter observations may be particularly relevant to human studies in which concomitant increases in PAI-1 levels and reductions in circulating PA activity have been associated with myocardial infarction.8,11,15

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Both circulating and clot-bound plasminogen activator inhibitor-1 inhibit endogenous fibrinolysis in the rat.

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