C-Reactive Protein Increases Plasminogen Activator Inhibitor-1 Expression and Activity in Human Aortic Endothelial Cells

Implications for the Metabolic Syndrome and Atherothrombosis

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Background—Inflammation plays a pivotal role in atherosclerosis. In addition to being a risk marker for cardiovascular disease, much recent data suggest that C-reactive protein (CRP) promotes atherogenesis via effects on monocytes and endothelial cells. The metabolic syndrome is associated with significantly elevated levels of CRP. Plasminogen activator inhibitor-1 (PAI-1), a marker of atherothrombosis, is also elevated in the metabolic syndrome and in diabetes, and endothelial cells are the major source of PAI-1. However, there are no studies examining the effect of CRP on PAI-1 in human aortic endothelial cells (HAECs).

Methods and Results—Incubation of HAECs with CRP results in a time- and dose-dependent increase in secreted PAI-1 antigen, PAI-1 activity, intracellular PAI-1 protein, and PAI-1 mRNA. CRP stabilizes PAI-1 mRNA. Inhibitors of endothelial NO synthase, blocking antibodies to interleukin-6 and an endothelin-1 receptor blocker, fail to attenuate the effect of CRP on PAI-1. CRP additionally increased PAI-1 under hyperglycemic conditions.

Conclusions—This study makes the novel observation that CRP induces PAI-1 expression and activity in HAECs and thus has implications for both the metabolic syndrome and atherothrombosis.

Key Words: inflammation ■ endothelium ■ thrombosis
PAI-1 is expressed in platelets, adipocytes, hepatocytes, monocytes, and smooth muscle cells, endothelial/hepatic. PAI-1 is primarily responsible for PAI-1 levels found in plasma.\(^{29,30}\) We have recently shown that CRP exerts a direct proinflammatory effect by decreasing eNOS activity and enhancing monocyte adhesion to human aortic endothelial cells (HAECs).\(^{14}\) However, there are no studies examining the effect of CRP on PAI-1 expression in HAECs. To additionally understand the effect of CRP on mediators of atherothrombosis, we tested the effect of CRP on PAI-1 expression and activity in HAECs.

**Methods**

For all the experiments, HAECs (Clonetics) were used between 3 to 5 passages. Purity of recombinant human CRP (Calbiochem) was checked by SDS-PAGE, yielding a single band when 1 \(\mu\)g was loaded on the gel. Endotoxin was removed from CRP with Detoxigel column (Pierce Biochemicals) and found to be <0.125 EU/mL (<12.5 pg/mL) by Limulus assay (BioWhittaker), as described previously.\(^{14}\) All media were tested for endotoxin and found to have <0.125 EU/mL.

HAECs (\(1 \times 10^6\) cells/mL) were used for all assays and incubated with different concentrations of CRP (ranging from 0 to 50 \(\mu\)g/mL) for the different times (3 to 24 hours). Cell viability, assessed by the MTT assay, was checked by SDS-PAGE, yielding a single band when 1 \(\mu\)g was loaded on the gel. Endotoxin was removed from CRP with Detoxigel column (Pierce Biochemicals) and found to be <0.125 EU/mL (<12.5 pg/mL) by Limulus assay (BioWhittaker), as described previously.\(^{14}\) All media were tested for endotoxin and found to have <0.125 EU/mL.

**Figure 1.** Effect of CRP on secreted PAI-1 antigen levels in HAECs. HAECs were incubated with CRP (0 to 50 \(\mu\)g/mL) for 3 to 12 hours. Secreted PAI-1 antigen levels were measured in cell supernates, as described in Methods. Data are presented of mean±SD of 5 experiments in triplicate.

**Figure 2.** Effect of CRP on PAI-1 activity in HAECs. HAEC were incubated with CRP (0 to 50 \(\mu\)g/mL) for 12 hours. PAI-1 activity levels were measured as described in Methods. Data are presented of mean±SD of 5 experiments in duplicate.

**Figure 3.** Effect of polymixin B and trypsinized CRP on secreted PAI-1 antigen in HAECs. HAECs were incubated with CRP (50 \(\mu\)g/mL) or polymixin B (25 \(\mu\)g/mL) plus CRP (50 \(\mu\)g/mL) or trypsinized CRP (50 \(\mu\)g/mL) for 12 hours. Secreted PAI-1 antigen levels were measured as described in Methods. Data are presented of mean±SD of 3 experiments in duplicate.

PAI-1 mRNA was assessed by first-strand cDNA synthesis followed by reverse transcriptase–polymerase chain reaction (RT-PCR), and the ratio of PAI-1/GAPDH was analyzed. Briefly, RNA was isolated using TRizol (Invitrogen), and 5 \(\mu\)g was used for first-strand cDNA synthesis (Invitrogen). cDNA (100 ng) was amplified using primers (Integrated DNA Technologies) specific for PAI-1 (forward: 5’-GCA CAA TCC CCC ATT CTA CG-3’; reverse: 5’-TCT AGA CGG CAG GTC TCC TGG ACC C-3’). PAI-1 was amplified for 30 cycles and GAPDH for 20 cycles. PAI-1 mRNA stability experiments were conducted using actinomycin D (10 \(\mu\)g/mL) as described previously.\(^{14}\)

To determine if CRP uptake in HAECs is receptor-mediated, HAECs were incubated with 10 to 50 \(\mu\)g/mL CRP for up to 120 minutes at 4°C in PBS with 0.1% azide, which blocks internalization. At the respective time points, FITC-labeled antibodies to CD32 and CD64 (Caltag, Pharmingen) were added, and an additional incubation was undertaken.\(^{15}\) The cells were analyzed by flow cytometry to determine the abundance of CD32 and CD64. Irrelevant isotype controls were added to check for nonspecific binding. All experiments except the receptor binding were performed on at least 3 occasions in duplicate or triplicate. Data are presented as

\[\text{PAI-1 Activity (U/mL)}\]
Figure 4. Effect of CRP on intracellular PAI-1 protein levels in HAECs. HAEC were incubated with CRP (5 to 50 μg/mL) for 12 hours. Western blotting for intracellular PAI-1 protein or β-actin (as loading control) was performed as described in Methods (A). Lane 1, control; lane 2, CRP 5 μg/mL; lane 3, CRP 10 μg/mL; lane 4, CRP 25 μg/mL; and lane 5, CRP 50 μg/mL. Intracellular PAI-1 protein/β-actin ratio is provided in panel B. *P<0.01 compared with control.

Figure 5. Effect of CRP on PAI-1 mRNA levels in HAECs. HAECs were incubated with CRP (5 to 50 μg/mL) for 6 hours. RT-PCR for PAI-1 mRNA or GAPDH mRNA (as loading control) was performed as described in Methods (A). Lane 1, control; lane 2, CRP 5 μg/mL; lane 3, CRP 10 μg/mL; lane 4, CRP 25 μg/mL; and lane 5, CRP 50 μg/mL. PAI-1/GAPDH ratio is provided in panel B. *P<0.01 compared with control.
mean ± SD. ANOVA was performed to assess significant differences with different doses of CRP. Wilcoxon signed-rank tests were used to compute differences in the variables, and the level of significance was set at $P < 0.05$.

**Results**

Incubation of HAECs with CRP at different time points (3, 6, 12, and 24 hours) resulted in a maximum increase in secreted PAI-1 antigen levels at 12 hours (Figure 1). Also, PAI-1 activity was significantly increased at 12 hours after incubation with CRP (Figure 2). Boiling of CRP (100°C for 1 hour) abolished its effect on secreted PAI-1 antigen (data not shown). Furthermore, coincubation of CRP with polymyxin B (25 μg/mL) did not abrogate its effect on PAI-1, whereas trypsinization of CRP abrogated its effect on PAI-1, suggesting that this effect was attributable to CRP but not lipopolysaccharide (Figure 3). Also, lipopolysaccharide (up to 100 μg/mL) failed to stimulate secreted PAI-1 antigen in HAECs. Western blotting for intracellular PAI-1 protein showed that CRP (5 to 50 μg/mL) caused a dose-dependent increase in intracellular PAI-1 protein, which was maximal at 12 hours with no change in β-actin levels (Figure 4). Also, incubation of HAECs with CRP resulted in a dose-dependent increase of PAI-1 mRNA levels as determined by PAI-1 RT-PCR using GAPDH as internal control (Figure 5). PAI-1 mRNA was maximally increased at 6 hours. Furthermore, CRP significantly increased PAI-1 mRNA stability (control, $t_{1/2}$: 15 hours; CRP 50 μg/mL, $t_{1/2}$: 18 hours; $P < 0.05$, n=3 experiments).

Because we had earlier shown that CRP decreases eNOS$^{14}$ and, furthermore, it has been shown that CRP activates ET-1 and IL-6 in human saphenous vein endothelial cells,$^{12}$ we tested the effects of these mediators on PAI-1 expression augmented by CRP. Inhibition of eNOS with l-NMMA (1 mmol/L) while decreasing eNOS in HAECs failed to affect PAI-1 expression (Figure 6). Similarly, the ET-1 receptor blocker (bosentan, 10 μmol/L) failed to have any effect on PAI-1 expression; blocking antibodies to IL-6 (5 μg/mL) did not have any effect on PAI-1 expression (Figure 6) but decreased IL-6 levels. In preliminary experiments (n=2), we show that CRP binds to both CD32 and CD64 in HAECs. Binding was maximum at 90 minutes and saturable at CRP levels of 50 to 100 μg/mL.

Because PAI-1 is increased in the metabolic syndrome and diabetes,$^{26,27,36–42}$ we examined the effect of CRP under high-glucose conditions (25 mmol/L) on PAI-1 expression. CRP significantly increased secreted PAI-1 levels additionally under hyperglycemic conditions (C-765±149 ng/mL; CRP 50 μg/mL to 1183±171 ng/mL; CRP 50 μg/mL plus HG 25 mmol/L to 1455±174 ng/mL; $P < 0.005$ by ANOVA; Figure 7).

**Discussion**

In addition to being a risk marker for cardiovascular disease, several lines of evidence point to a proatherogenic role for CRP.$^{2–14}$ CRP has been shown to exert proinflammatory effects in endothelial cells. Endothelial PAI-1 seems to be primarily responsible for PAI-1 levels in plasma.$^{29,34}$ CRP levels and PAI-1, a marker of atherothrombosis, are increased in subjects with the metabolic syndrome and diabetes. Furthermore, both PAI-1 and CRP levels seem to be elevated and
cosegregate with the different features of the metabolic syndrome. However, there are no studies examining the effect of CRP on PAI-1 in HAECs or adipocytes.

Because we have previously shown that CRP decreases eNOS in HAECs and previous work has shown that CRP stimulates cell-adhesion molecules, monocyte chemotactic protein-1, and monocyte-endothelial cell adhesion, in the present study, we tested the hypothesis that CRP could promote expression and activity of PAI-1 in HAECs.

We first tested the effect of CRP on secreted PAI-1 antigen levels as well as activity in HAECs. CRP significantly increased secreted and intracellular PAI-1 antigen as well as activity in HAECs in a dose-dependent manner. Also, it is important to note that all reagents and media used were free of endotoxin (<12.5 pg/mL); addition of polymixin B did not affect the of effects CRP on PAI-1. Ballou et al. have previously shown that CRP induces monocyte proinflammatory cytokine release and that addition of polymixin B did not abrogate its effect, thus ruling out the effect of endotoxin contribution to the proatherogenic effects of CRP. Furthermore, lipopolysaccharide (100 pg/mL) at a concentration far in excess of any contamination present in our CRP preparations (<12.5 pg/mL) failed to stimulate PAI-1 levels in HAECs. The effect of CRP on PAI-1 antigen and activity levels was maximal at 12 hours. It has previously been reported by Kooistra et al. that PAI-1 released from endothelial cells is rapidly inactivated because of production of substrate tPA by endothelial cells. Furthermore, aortic endothelial cells produce 20 times more PAI-1 than HUVECs, and the amount of PAI-1 produced by HAECs increases from passages 1 to 4; thus HAECs are a good model to study the regulation of PAI-1. All of our experiments were conducted within 5 passages of cells.

It seems that the effect of CRP on PAI-1 levels is at the transcriptional level. Our studies show that CRP augments the stability of PAI-1 mRNA. Previously, insulin and cytokines have been shown to augment PAI-1 release via increasing mRNA stability in BAECs.

To obtain mechanistic insights into the effects of CRP on PAI-1 in HAECs, we performed inhibitor studies. CRP has been shown to augment endothelin-1 (ET-1) and interleukin 6 (IL-6) and thereby contribute to increased ICAM-1, VCAM-1, and MCP-1 in human saphenous vein endothelial cells. In our system (HAECs), in addition to CRP failing to augment ET-1/IL-6 levels, an ET blocker or IL-6–blocking antibodies failed to affect PAI-1 expression and activity. Thus, it is clear that different mechanistic pathways operate in different cell systems, ie, venous versus aortic endothelium.

Because the aortic endothelium is the primary site for atherosclerosis, it is prudent to study the effects of CRP in these cells. Because CRP decreases eNOS expression and activity in HAECs, we examined the effect of l-NMMA on PAI-1 expression. l-NMMA, although decreasing eNOS protein, failed to have any effect on PAI-1 expression. Fcγ receptors have been shown to be the major receptors for CRP on leukocytes and are absent in venous endothelium. Thus, the reported effects on venous endothelium may not be receptor-mediated. In preliminary data, we show that CD32 and CD64 seem to be the receptors for CRP in HAECs, and future detailed studies will delineate the major receptor accounting for the effect of CRP on HAECs.

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**Figure 7.** Effect of CRP and hyperglycemia (HG) on Intracellular PAI-1 in HAECs. HAECs were incubated with CRP (50 μg/mL) in euglycemic (5.5 mmol/L) or hyperglycemic (25 mmol/L) conditions for 12 hours, and PAI-1 levels were determined by Western blotting, as described in Methods (A). Lane 1, control; lane 2, CRP 25 μg/mL; lane 3, CRP50 μg/mL; lane 4: HG; lane 5: HG+CRP 25 μg/mL; and lane 6: HG+CRP 50 μg/mL. Intracellular PAI-1 protein/β-actin ratio is provided in panel B. *P<0.01 compared with control; *a P<0.05 compared with HG.
The metabolic syndrome seems to be a major risk factor for cardiovascular disease, and numerous studies have now confirmed that CRP levels are elevated in patients with the metabolic syndrome and diabetes. In the Insulin Resistance and Atherosclerosis Study (IRAS), PAI-1 and CRP showed strong correlations with development of diabetes. Unlike fibrinogen and CRP, the association of PAI-1 to incident diabetes was particularly strong and independent of other known factors associated with diabetes. The authors suggested that both PAI-1 levels and CRP levels may be common antecedents for the metabolic syndrome and atherosclerosis and may do so by promoting chronic inflammation (common soil hypothesis). Increased levels of PAI-1 have been shown to be correlated with insulin resistance, so that increased plasma PAI-1 levels are now considered one of the features of the metabolic syndrome. Chronic hyperglycemia is associated with increased PAI-1 localization in the aortic wall and have found greater PAI-1 content in atheroma specimens of diabetics. Thus, it is very interesting that in our studies, in presence of high glucose, PAI-1 expression and activity is augmented additionally by CRP in HAECs. Thus, given that both CRP and PAI-1 are present in the atherosclerotic lesion, augmentation of PAI-1 by CRP, especially under hyperglycemic conditions, could have a negative impact on vascular remodeling.

The present study points to a pivotal role for inflammation as assessed by increased CRP and increased PAI-1 levels, which seems to be the underpinning of atherothrombosis, especially in the metabolic syndrome and the diabetic state. Future studies will unravel other mechanisms by which CRP orchestrates this novel biological effect in endothelial cells.

Acknowledgments

This study was supported by grants from the NIH K24 AT00596 (to Dr. Jialal), Juvenile Diabetes Foundation (to Dr. Jialal), and American Diabetes Association (to Dr. Devraj).

References


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_Circulation_, published online January 6, 2003;

_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2003 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

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