Objective—Plasmin activates several proinflammatory pathways at the cellular level in vitro. Lipopolysaccharide (LPS) administration to healthy humans results in a rapid generation of plasmin activity, accompanied by activation of a number of inflammatory systems.

Methods and Results—To determine the role of early plasmin activity in LPS-induced inflammation in vivo, 16 healthy males received an intravenous bolus injection with LPS (from *Escherichia coli*, 4 ng/kg) directly preceded by a 30-minute intravenous infusion of tranexamic acid (2 g, n=8), a plasmin activation inhibitor, or placebo (n=8). LPS injection induced marked increases in the plasma levels of D-dimer and plasmin-α2-antiplasmin complexes, indicative of plasmin activation and generation, respectively, which were strongly attenuated by tranexamic acid (both *P*<0.01 versus placebo). However, tranexamic acid did not influence LPS-induced coagulation activation, granulocytosis, neutrophil activation (expression of CD11b, CD66b, and L-selectin) or degranulation (plasma concentrations of elastase-α1-antitrypsin and bactericidal permeability-increasing protein), endothelial cell activation (plasma levels of von Willebrand factor and soluble E-selectin), or cytokine release.

Conclusion—These data argue against a role of early plasmin generation in the subsequent activation of other inflammatory pathways during human endotoxemia. (Arterioscler Thromb Vasc Biol. 2004;24:483-488.)

Key Words: fibrinolysis ■ coagulation ■ vascular biology

Lipopolysaccharide (LPS), present in the outer membrane of Gram-negative bacteria, plays a pivotal role in triggering inflammatory responses during Gram-negative sepsis. The human endotoxemia model, in which a bolus dose of LPS is administrated intravenously to healthy subjects, has been frequently used to study the mechanisms by which inflammatory systems are activated in humans in vivo. Intravenous injection of LPS into healthy humans is associated with activation of the fibrinolytic system, the coagulation cascade, neutrophil granulocytes, endothelial cells, and the cytokine network. In particular, activation of fibrinolysis is a very early phenomenon in the human response to LPS administration. Within two hours a marked increase in tissue-type plasminogen activator (tPA) can be detected, which leads to the generation of plasmin as reflected by an increase in plasmin-α2-antiplasmin (PAP) complexes. This activation is rapidly followed by an increase in plasminogen activator inhibitor-1 (PAI-1) levels, inhibiting the fibrinolytic system. These fibrinolytic changes precede and occur independently from activation of the coagulation system in this model.

Recent evidence indicates that the fibrinolytic system likely has functions different from its classical fibrin dissolving properties. Binding of plasmin(ogen) to surfaces plays a pivotal role in regulating the function of this system. Besides binding to fibrin, plasmin(ogen) can bind to many cell types, including neutrophilic granulocytes, monocytes, lymphocytes, platelets, and endothelial cells. On binding to cells, conversion of plasminogen to plasmin is facilitated, and cell-bound plasmin is protected from inactivation by α2-antiplasmin. Although the biological function of cell-bound plasmin has been regarded mainly in terms of fibrinolytic activity, in recent years it has become clear that plasmin can affect various cell functions. Cell-associated plasmin is considered to play an important role in extracellular matrix degradation and tissue remodeling. Interestingly, plasmin can also induce proinflammatory responses independent of its proteolytic properties. In vitro, plasmin was demonstrated to stimulate the release of cytokines and other inflammatory mediators by different cell types. Furthermore, plasmin induced cell adhesion and migration in vitro, and studies using plasminogen-deficient mice have provided in vivo evidence that plasma plasmin is involved in the regulation of leukocyte adhesion.
evidence for an essential role of the plasminogen system in cell migration toward inflammatory sites.\textsuperscript{21,22} Moreover, plasmin can activate the p38 mitogen-activated protein kinase (MAPK) signaling pathway in monocytes,\textsuperscript{14,23} and activation of this pathway was recently shown to be of key importance for the inflammatory response to LPS in humans.\textsuperscript{24,25} Together, these findings implicate plasmin as a mediator of several cellular inflammatory responses. However, at present, the role of plasmin in systemic inflammation in vivo is unknown.

Tranexamic acid (Cyklokapron) is a synthetic antifibrinolytic substance, which acts by competitively blocking the lysine binding sites of plasmin(ogen), thereby preventing binding to fibrin or cells.\textsuperscript{26} In vitro, tranexamic acid potently inhibited plasmin-induced proinflammatory responses.\textsuperscript{13,19,27}

The fact that the formation of plasmin is one of the earliest-occurring events after intravenous administration of LPS, together with the recent findings that plasmin is able to induce several cellular proinflammatory responses, including activation of p38 MAPK, led us to hypothesize that plasmin may play a role in the induction of LPS-induced inflammatory pathways. To test this hypothesis, we studied the effect of tranexamic acid infusion on activation of coagulation, granulocytes, endothelial cells, and the cytokine network in healthy humans injected with a single dose of LPS.

**Methods**

**Study Design**

Sixteen healthy men (19 to 34 years of age) were studied. The study was approved by the institutional scientific and ethics committees, and written informed consent was obtained from all volunteers. Tranexamic acid (Cyklokapron; Pharmacia & Upjohn) (2 g in 100 mL sterile NaCl 0.9%; N=8) or placebo (100 mL 0.9% sterile NaCl; N=8) was administered intravenously over 30 minutes directly prior to LPS injection. All participants received a bolus intravenous injection of LPS (Escherichia coli lipopolysaccharide, lot G; US Pharmacopoeia, Rockville, MD) at a dose of 4 ng/kg. Oral temperature, blood pressure, heart rate, and oxygen saturation were measured at half-hour intervals (Dinamap1846 SX; Critikon). Clinical symptoms such as headache, chills, nausea, and myalgia were recorded throughout the study periods using a graded scale (0, absent; 1, weak; 2, moderate; 3, severe).

**Blood Collection**

Blood was obtained before and at the end of the infusion of tranexamic acid or placebo (t=−0.5 hour and t=0 hour), and at 0.5, 1, 1.5, 2, 3, 4, 5, 6, 8, and 23 hours after LPS injection. All blood samples, except those for the determination of leukocyte counts and differentials, were centrifuged at 3000 rpm for 15 minutes at 4°C, and plasma was stored at −20°C until assays were performed. Blood for fluorescence-activated cell sorter (FACS) analysis was obtained directly before tranexamic acid or placebo infusion (t=−0.5 hour) and at 1, 4, 6, and 23 hours after LPS administration, and was put on ice.

**Assays**

Coagulation and fibrinolysis assays were done using citrated plasma, with all other assays using EDTA plasma. The following ELISAs were performed according to the instructions of the manufacturer and/or as described: D-dimer, F1+2 prothrombin fragment and thrombin-antithrombin (TAT) complexes (all Dade Behring), IPA (Asserachrom tPA, Diagnostics Stago), PAI-1 (Monozyme), and Elastase-α1-antitrypsin complex concentrations were measured with an ELISA modified from a radioimmunoassay (RIA) procedure as described,\textsuperscript{28} bactericidal permeability-increasing protein (BPI),\textsuperscript{29} von Willebrand Factor (vWF) (Dako), soluble E-selectin (Diacalone), tumor necrosis factor (TNF)-α, IL-6, IL-10, and IL-8 (all Central Laboratory of the Netherlands Red Cross Blood Transfusion Service), PAP complexes were measured by RIA as described.\textsuperscript{30} Leukocyte counts and differentials were assessed by using a STKR Coulter counter (Beckman Coulter).

**Flow Cytometry**

Erythrocytes were lysed with ice-cold isotonic NH\textsubscript{4}Cl solution (155 mmol/L NH\textsubscript{4}Cl, 10 mmol/L KHCO\textsubscript{3}, 0.1 mmol/L EDTA [pH 7.4]) for 10 minutes. The cells were centrifuged at 250 g for 10 minutes at 4°C. The remaining cells were washed twice with FACS buffer (PBS supplemented with 0.5% BSA, 0.01% NaN3, and 0.35 mmol/L EDTA) and brought to a concentration of 4×10\textsuperscript{6} cells/mL. All procedures were performed at 4°C. All FACS reagents were titrated to obtain optimal results, as recommended by the manufacturers. For each test at least 10\textsuperscript{4} cells were analyzed using a FACS Calibur flow cytometer (Becton Dickinson). Cell surface staining was performed using the following anti-human monoclonal antibodies: FITC-labeled mouse anti-human CD66b (clone 80H3; Immunotech), PE-labeled mouse anti-human L-selectin (clone DREG-56, BD Pharmingen), and APC-labeled mouse anti-human CD11b (clone ICRF44) (BD Pharmingen). To correct for nonspecific staining, all analyses were also conducted with the appropriate isotype control antibodies (FITC-, PE-, and APC-labeled mouse IgG1; BD Pharmingen). Granulocytes were identified by forward and side-angle light scatter gating. Data are presented as the difference between mean fluorescence intensities (MFI) of specifically and nonspecifically stained cells.

**Statistical Analysis**

All values are given as mean±SEM. Differences in time and between treatment groups were analyzed by mixed models analysis using SPSS for Windows (SPSS 11.5). A value of P<0.05 was considered to represent a statistically significant difference.

**Results**

**Clinical Features**

Intravenous injection of LPS elicited a febrile response, peaking after 4 hours (38.4±0.3°C), together with tachycardia and transient flu-like symptoms, including headache, chills, nausea, and myalgia. Infusion of tranexamic acid did not influence LPS-induced signs and symptoms, and no adverse events attributable to tranexamic acid infusion were observed (data not shown).

**Inhibition of Plasmin Activity by Tranexamic Acid**

Tranexamic acid competitively binds to the high affinity lysine binding sites on plasmin(ogen), thereby preventing direct action of plasmin on fibrin and cells and the surface-facilitated conversion of plasminogen to plasmin. To obtain evidence for the in vivo plasmin inhibitory activity of tranexamic acid during endotoxemia, we determined the plasma concentrations of D-dimer, a split product cleaved off from cross-linked fibrin by a direct action of plasmin, as a measure for plasmin activity, and the plasma levels of PAP complexes, as a measure for plasmin generation (Figure 1). LPS administration resulted in a profound rise in D-dimer, which reached a plateau phase from 3 hours and peaked at 8 hours (3400±1000 μg/L), and a transient rise in PAP complexes, peaking after 1.5 hours (276±57 nmol/L). Tranexamic acid essentially prevented the increase in D-dimer levels (8 hours: 1554±388 μg/L; P<0.01 versus placebo).
and blunted the rise in PAP complexes (peak at 2 hours: 172±46 nmol/L; \( P < 0.01 \) versus placebo). Hence, these data indicate that tranexamic acid effectively inhibited plasmin generation and activity.

**Activation and Inhibition of Fibrinolysis**

LPS injection resulted in an early stimulation of the fibrinolytic system (Figure 2), measured by a rise in tPA levels, peaking after 3 hours (\( P < 0.001 \) versus baseline). This increase in tPA levels was followed by the secretion of its inhibitor, PAI-1, peaking after 4 hours (\( P < 0.001 \) versus baseline). Consistent with its mode of action, tranexamic acid did not influence the LPS-induced rises in tPA and PAI-1 concentrations.

**Activation of the Coagulation System**

LPS administration was associated with thrombin generation, as reflected by increases in the plasma levels of the prothrombin fragment F1+2 and TAT complexes (both \( P < 0.001 \) versus baseline). Tranexamic acid did not affect the LPS-induced thrombin generation (Figure 3).

**Leukocyte Activation**

LPS injection induced activation of neutrophilic granulocytes, as reflected by a biphasic change in neutrophil counts involving an initial decrease with a nadir at 1 hour followed by neutrophilia peaking at 8 hours (\( P < 0.001 \) versus baseline; Figure 4). Furthermore, LPS administration induced an upregulation of the activation markers CD11b (Figure 4) and CD66b (data not shown) at the surface of circulating granulocytes, with a concurrent downmodulation of L-selectin (Figure 4) (all \( P < 0.01 \) versus baseline). Moreover, LPS injection resulted in an increase in degranulation products as measured by BPI (Figure 4) and elastase-\( \alpha \)-1-antitrypsin complexes (data not shown) (both \( P < 0.001 \) versus baseline). Tranexamic acid did not modify any of these LPS-induced changes.

**Endothelial Cell Response**

LPS administration elicited endothelial cell activation, as indicated by profound increases in the plasma concentrations of vWF and soluble E-selectin (both \( P < 0.001 \) versus baseline). Tranexamic acid infusion did not alter these LPS-induced endothelial cell responses (Figure 5).

**Cytokine Response**

LPS injection was associated with a transient rise in the plasma concentration of TNF, IL-6, IL-8, and IL-10, peaking after 2 to 3 hours (all \( P < 0.001 \) versus baseline). Tranexamic acid infusion did not influence these LPS-induced cytokine responses (Figure 6).

**Discussion**

In recent years it has become clear that plasmin has functions beyond its classical proteolytic and fibrin degrading properties. In vitro and animal studies have provided evidence for a stimulatory effect of plasmin on cellular proinflammatory responses. The current investigation is the first to examine the role of plasmin during a systemic inflammatory response in humans in vivo. We demonstrate that although pretreatment with tranexamic acid strongly inhibited LPS-induced plasmin activation, it did not influence sensitive markers of the
activation of proinflammatory pathways that accompany endotoxemia, including effects on the coagulation cascade, granulocytes, endothelial cells, and the cytokine network. These findings suggest that plasmin is not involved in the induction of systemic inflammatory responses during human endotoxemia.

Binding of plasmin(ogen) to fibrin or cell surfaces is of crucial importance in regulating its function. Plasmin(ogen) binds to fibrin and cells via its lysine binding sites, which are associated with its kringle domains and recognize carboxy-terminal lysines of surface proteins. Upon binding, plasmin activity is increased, and the conversion of plasminogen to plasmin is facilitated. Tranexamic acid competently binds to the lysine binding sites of plasmin(ogen), thereby blocking the binding to fibrin and cells. Although plasmin can still be formed under these circumstances, its activity and the surface-facilitated plasmin generation are inhibited. In line with this mode of action, we found that pretreatment with tranexamic acid strongly reduced the LPS-induced rise in the plasma levels of D-dimer, a split product cleaved off from cross-linked fibrin by a direct action of plasmin, providing direct evidence for the virtually complete inhibition of plasmin activity on fibrin in vivo. Furthermore, pretreatment with tranexamic acid decreased the levels of circulating PAP complexes, indicating that apart from the strong inhibition of plasmin activity, plasmin generation was also inhibited by tranexamic acid, albeit to a lesser extent. As expected, pretreatment with tranexamic acid did not influence the LPS-induced increase in tPA levels, nor did it change the subsequent rise in PAI-1 concentration.

LPS injection induced thrombin generation, as shown by a rise in the plasma concentrations of F1+2 and TAT complexes, which indicates stimulation of the coagulation cas-

Figure 3. Activation of coagulation. Plasma concentrations of F1+2 and TAT complexes after LPS administration (4 ng/kg IV, t=0 hour), preceded by a 30-minute infusion of placebo or tranexamic acid (2 g IV, ●). Data are mean±SEM. P values (NS, not significant) indicate the difference between treatment groups.

Figure 4. Activation of neutrophils. Circulating neutrophil counts, mean fluorescence intensity (MFI) of CD11b and L-selectin on granulocytes and the degranulation product BPI after LPS administration (4 ng/kg IV, t=0 hour), preceded by a 30-minute infusion of placebo or tranexamic acid (2 g IV, ●). Data are mean±SEM. FACS data (CD11b and L-selectin) are expressed as the difference between specific MFI and nonspecific MFI. P values (NS, not significant) indicate the difference between treatment groups.

Figure 5. Endothelial cell activation. Plasma concentrations of vWF and soluble E-selectin after LPS administration (4 ng/kg IV, t=0 hour), preceded by a 30-minute infusion of placebo or tranexamic acid (2 g IV, ●). Data are mean±SEM. P values (NS, not significant) indicate the difference between treatment groups.
Our findings show that infusion of tranexamic acid does not influence the neutrophilic responses to LPS administration in humans in vivo and has no effect on neutrophil activation, as reflected by unaltered upregulation of CD11b and CD66b, downmodulation of L-selectin, and rise in circulating neutrophil degranulation products.

Endothelial cells play a pivotal role in the inflammatory response to systemic infection.37,38 Plasmin can influence endothelial cell behavior in vitro. Endothelial cells incubated with plasmin showed an enhanced release of arachidonate, the precursor of leukotriene B4 (LTB4) and other eicosanoids,16 which was inhibited by tranexamic acid.

Furthermore, plasmin induced endothelial cell retraction, evidenced by loss of cell–cell contacts and increased permeability,17 and stimulated endothelial cell migration in vitro.18 Together, these data implicate plasmin as a mediator of endothelial cell activation. However, in the present study, inhibition of LPS-induced plasmin activity did not affect the endothelial cell activation, measured by plasma levels of vWF and soluble E-selectin.

The release of cytokines into the circulation is a characteristic feature of endotoxemia, predominantly mediated by monocytes and macrophages. Stimulation of human peripheral monocytes with plasmin in vitro induced an upregulation of several inflammatory mediators, including TNF-α, IL-1α, IL-1β, monocyte chemoattractant protein (MCP)-1, and LTB4.13–15 Plasmin-induced expression of TNF-α, IL-1α, and IL-1β involved activator protein-1 (AP-1) and nuclear factor-kB (NF-kB) activation,13 whereas plasmin-induced monocyte expression of MCP-1 and CD40 was triggered via activation of the p38 MAPK and Janus Kinase/signal transducer and activator of transcription (STAT) signaling pathways.14 Syrovets et al demonstrated that ciglitazone inhibited cytokine release from plasmin-stimulated monocytes by inhibition of AP-1 and NF-kB activation via modulation of p38 MAPK activity.21 In accordance with this finding, a specific p38 MAPK inhibitor significantly diminished proinflammatory gene expression by plasmin-stimulated peripheral monocytes.23 Together, these data indicate that plasmin induces monocytic cytokine production at least in part via p38 MAPK activation. Recently, our laboratory demonstrated that the p38 MAPK signaling pathway is important for induction of the inflammatory response to LPS in humans. Indeed, intravenous injection of LPS resulted in a transient activation of p38 MAPK,24 and more importantly, a specific p38 MAPK inhibitor strongly inhibited the LPS-induced cytokine production and other proinflammatory responses in humans in vivo.24,25 In spite of this abundant in vitro evidence that plasmin can induce p38 MAPK activation and cytokine production, inhibition of plasmin activity by tranexamic acid did not affect the cytokine response in the present study. It should be noted that we did not measure p38 MAPK activation in blood cells in the current study, and thus we can only speculate on the effects of tranexamic acid on p38 MAPK activation in our study subjects. Indeed, in a more general way, it remains to be established whether plasmin can activate p38 MAPK in vivo.

In vitro and animal studies have indicated that plasmin can activate various inflammatory pathways implicated in the host response to endotoxemia. We here demonstrate that although
active plasmin is generated early after intravenous injection of LPS into normal subjects, it does not contribute to a significant extent to activation of the coagulation system, granulocytes, the vascular endothelium, or the cytokine network. By the nature of our experiment, performed in healthy human beings, we cannot exclude that plasmin does play a role in endotoxemia or infection models in which more severe challenges are given. Investigations in animals are warranted to determine the potential role of plasmin in a lethal systemic inflammatory response syndrome.

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Inhibition of Plasmin Activity by Tranexamic Acid Does Not Influence Inflammatory Pathways During Human Endotoxemia

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