Inhibition of Factor XII in Septic Baboons Attenuates the Activation of Complement and Fibrinolytic Systems and Reduces the Release of Interleukin-6 and Neutrophil Elastase


In previous studies, we have shown that administration of monoclonal antibody (MoAb) C6B7 against human factor XII to baboons challenged with a lethal dose of Escherichia coli abrogates activation of the contact system and modulates secondary hypotension. To evaluate the contribution of activated contact proteases to the appearance of other inflammatory mediators in this experimental model of sepsis, we studied the effect of administration of MoAb C6B7 on activation of complement and fibrinolytic cascades, stimulation of neutrophil degranulation, and release of the proinflammatory cytokines, tumor necrosis factor-α (TNF-α) and interleukin-6 (IL-6). Activation of the complement system, as reflected by circulating C3b/c and C4b/c levels, was significantly reduced in five animals that had received MoAb C6B7 before a lethal dose of E coli as compared with five control animals that had been given a lethal challenge only. Inhibition of contact activation also modulated the fibrinolytic response, since the release of tissue-type plasminogen activator (t-PA) and the appearance of plasmin-α2-antiplasmin (PAP) complexes into the circulation was significantly attenuated upon pretreatment with anti-factor XII MoAb.

The contact system, consisting of the zymogens factor XII (Hageman factor), prekallikrein, factor XI, and the substrate procofactor, high–molecular-weight kininogen,1 has been shown to participate in various physiological and pathological processes, such as blood coagulation, fibrinolysis, and the inflammatory response. The activation of the contact system leads to the generation of various biologically active components, including kininogens, which are substrates for the convertases of the contact system.

Interactions between the contact system and other inflammatory systems, such as the complement and fibrinolytic systems, have been implicated in the pathogenesis of sepsis. The complement system, including the regulatory proteins C3b and C4b, is activated in sepsis and plays a role in the recruitment of neutrophils and monocytes to the site of infection. The fibrinolytic system, consisting of tissue-type plasminogen activator (t-PA) and plasminogen activator inhibitor (PAI), is also activated in sepsis, leading to the generation of plasmin, which can degrade fibrin and other extracellular matrix components.

The contact system is also involved in the generation of kininogens, which are converted to kinins by the action of the convertases of the contact system. The kinins, such as bradykinin, are potent vasodilators and can modulate the inflammatory response by stimulating the release of cytokines and other mediators. The contact system also interacts with the complement system, including the regulatory proteins C3b and C4b, which are activated in sepsis and play a role in the recruitment of neutrophils and monocytes to the site of infection. The fibrinolytic system, consisting of tissue-type plasminogen activator (t-PA) and plasminogen activator inhibitor (PAI), is also activated in sepsis, leading to the generation of plasmin, which can degrade fibrin and other extracellular matrix components.

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aim of the present study was to evaluate in sepsis whether activation of factor XII and the contact system may contribute to activation of the complement and fibrinolytic cascades and stimulation of neutrophils and monocytes. For this, we analyzed serial blood samples from these animals using assays reflecting activation of these plasma proteases and blood cells. Our results indicate that inhibition of factor XII by MoAb C6B7 may modulate the inflammatory response during lethal sepsis at various levels.

**MATERIALS AND METHODS**

**Preparation of MoAb C6B7.** The murine MoAb C6B7 (IgG-κ) raised against the light chain of human factor XII fragment (factor XII, β-factor XIIa) was purified from ascitic fluid under sterile conditions as previously described. MoAb C6B7 can inhibit the coagulant activity of factor XII in vitro and retard cleavage of high-molecular-weight kininogen after contact activation of plasma induced by dextran sulfate. In vivo, it modulated the decrease of high-molecular-weight kininogen and inhibited the formation of kallikrein-α2-macroglobulin complexes, indicating contact system inhibition.

**Induction of sepsis in baboons and pretreatment with MoAb C6B7.** The baboon model of sepsis used in this study has been described in detail elsewhere. Briefly, E coli (organisms) type B were isolated, stored, reconstituted, and characterized as described by Hinshaw et al. A mixed breed of Papio c. cynocephalus/Papio c. anubis baboons was purchased from a breeding colony maintained by the University of Oklahoma Sciences Center Animal Facility at the Oklahoma City Zoo. The animals were transferred to the Oklahoma City Veterans Administration Hospital animal facility, where they were observed for a minimum of 10 days to ensure adequate equilibration before experimentation. A lethal dose of E coli (4 × 10^10 colony-forming units (CFU)/kg body weight) was given as a 2-hour intravenous infusion. Gentamycin was given at 9 mg/kg intravenously at 2 hours for 75 minutes, and at 4.5 mg/kg at 6 and 9 hours for 30 minutes. Gentamycin (4.5 mg/kg) was then given intramuscularly at the end of the experiment and twice daily for 3 days to surviving animals. Baboons that recovered from shock were observed daily and medically treated as appropriate. Surviving animals were euthanized after a minimum of 7 days with sodium pentobarbital. In the treatment group consisting of five animals, MoAb C6B7 was infused for 10 to 30 minutes to achieve a plasma concentration of 1 to 2 μg/mL before the lethal challenge with E coli, as previously described. The control group consisted of five animals that received E coli only. The course of the septic process, as well as activation patterns of the coagulation and contact systems in both groups, have been described in detail elsewhere.

Blood samples were obtained from the animals before E coli administration (t = 0) and at 1, 2, 3, 4, and 6 hours thereafter. Samples used for this study were collected in polypropylene tubes on 3.8% wt/vol sodium citrate and stored at −70°C until tests were performed. For the present study, samples from all animals of the treatment group and from four of five animals of the control group were available. We therefore added one lethal baboon to this study, resulting in a control group of five animals. The study protocol used received prior approval by the Institutional Animal Care and Use Committees of the Oklahoma Medical Research Foundation and the Oklahoma Health Sciences Centers, and was performed in adherence to National Institutes of Health guidelines for the use of experimental animals.

**Assays.** C3b/c in baboon plasma was assessed with a radioimmunoassay as reported previously. In short, MoAb anti-C3-28, which binds to a neoepitope expressed on human C3b, C3bi, and C3c, was used as a catching antibody, and polyclonal anti-human C3c as detecting antibodies. Results were expressed as a percentage of the amount of C3b/c present in normal baboon serum aged (NBA), ie, normal baboon serum (NBS) incubated for 7 days at 37°C in the presence of 0.02% (w/v) NaCl.

C4b/c in baboon plasma was assessed with an assay similar to that for C3b/c. In this radioimmunoassay, MoAb anti-C4-1, which binds to a neoepitope expressed on human C4b, C4bi, and C4c, was coupled to Sepharose and used as a catching antibody. Polyclonal anti-human C4 antibodies were used as detecting antibodies. Results were expressed as a percentage of C4b/c generated in NBS by incubation with heat-aggregated IgG (NBS-AHG), according to the method previously described for human serum.

**Tissue-type plasminogen activator (t-PA) and plasminogen activator inhibitor type 1 (PAI-1) concentrations were determined using enzyme-linked immunosorbent assays (ELISAs) as reported elsewhere.** The lower limits of detection of these assays were 3 and 5 ng/mL, respectively.

Plasmin-α2-antiplasmin (PAP) complex levels were determined by an ELISA that had been adapted from a previously described radioimmunoassay. Briefly, murine MoAb AAP-11, directed against complexed and inactivated α2-antiplasmin, was coated on microtiter plates. Bound complexes were detected by subsequent incubation with affinity-purified biotinylated polyclonal rabbit antibodies raised against human plasminogen. Levels of PAP complexes were expressed as a percentage of the level present in normal baboon plasma (NBP) in which a maximal amount of PAP complexes had been generated by addition of an equal volume of urokinase (50 μg/mL) in the presence of 0.4 μM methylamine to inactivate α2-macroglobulin, further referred to as NBP-MA-UK. The lower limit of detection of this assay was 0.1% of NBP-MA-UK.

Elastase-α1-protease inhibitor complexes were determined with a radioimmunoassay that has been described in detail elsewhere. Results were expressed as nanograms of elastase per milliliter by reference to a standard curve that consisted of NBP to which human neutrophil elastase (Elastin Products Co, Pacific, MO) was added at a final concentration of 2 μg/mL. In this standard, more than 95% of the elastase is complexed to α1-antitrypsin. The lower limit of detection was 5 ng/mL. Normal values are less than 100 ng/mL.

TNF-α and IL-6 concentrations were measured by ELISA as reported elsewhere. The lower limits of detection were 3.5 and 0.1 ng/mL, respectively.

Plasma endotoxin levels were assayed using a limulus amebocyte lysate assay (Pyrogent; BioWhittaker Inc, Walkersville, MD). The detection limit was 0.05 endotoxin units (EU)/mL. Bacterial viability counts in the inoculum and in freshly collected baboon samples 2 hours after the start of the challenge were determined by standard dilution techniques.

**Statistical analysis.** Values are expressed as the mean ± SEM. Between groups, a nonparametric statistical analysis was performed using Mann-Whitney U/Wilcoxon rank-sum test. A difference was considered significant at P < .05 and highly significant at P < .01 (two tailed).

**RESULTS**

**Complement activation.** Plasma levels of C3b/c and C4b/c were measured to estimate the extent of complement activation in this study. In the control group, a rapid increase of circulating levels of C3b/c was observed during the first 2 hours after the start of E coli infusion (Fig 1A), reaching maximum values of 11.6% ± 0.7% of maximally activated standard baboon serum (NBA). This increase was similar at 1 hour in the treatment group, but became significantly reduced thereafter, reaching peak levels of 6.4% ± 1.3% at 2 hours (Fig 1A). In both groups, C3b/c levels gradually de-
INHIBITION OF FACTOR XII IN SEPTIC BABOONS

Fig 1. Complement activation after lethal E coli infusion. Mean ± SEM plasma levels of C3b/c (A) and C4b/c (B) in control (●) and MoAb-treated (○) groups. C3b/c and C4b/c are expressed as a percentage of NBA and NBS-AHG, respectively. Differences between groups, determined by Wilcoxon/Mann-Whitney U test, are significant at *P < .05 and **P < .01.

clined after infusion of E coli had stopped, suggesting that part of the observed activation was triggered directly by E coli and/or endotoxin. In addition, since circulating levels of C4b/c immediately increased from t = 0 hours (Fig 1B), C3 activation may also have occurred to some extent via the classic pathway. Activation of C4 was protracted for at least 6 hours and reached a maximum of 12.6% ± 1.3% of maximally activated normal baboon serum (NBS-AHG) in control animals at the end of the observation period. Although a similar pattern of activation was observed in C6B7-treated baboons, C4b/c levels were significantly reduced at all time points. Thus, administration of MoAb C6B7 to baboons with lethal sepsis was associated with less complement activation.

Fibrinolytic response. In agreement with previous observations, a pronounced activation of fibrinolysis was observed with lethal E coli challenge (Fig 2A to C). Administration of MoAb C6B7 attenuated the appearance of t-PA and PAP complexes in the circulation. In the control group, plasma concentrations of t-PA started to increase at 1 hour and were consistently higher than levels observed in MoAb-treated animals (Fig 2A). Maximum levels of 47.8 ± 5.8 and 26.2 ± 5.0 ng/mL were measured at 6 hours in the control and treatment groups, respectively. Differences in t-PA levels between the groups reached statistical significance at 4 and 6 hours. Concentrations of circulating PAP complexes, which reflect generation of plasmin, the key enzyme of the fibrinolytic system, increased from baseline levels at 1 hour and reached a peak value of 13.2% ± 2.5% of fully activated standard plasma (NBP-MA-UK) at 2 hours (Fig 2B) in control animals. In contrast, in the anti-factor XII-treated group, PAP complexes only moderately increased to a maximum of 6.0% ± 2.0% at 3 hours. PAP levels were significantly different between the groups at 1, 3, and 4 hours. Notably, in this model, a 2-hour infusion of E coli resulted in generation of approximately fivefold more plasmin than observed previously after a lethal bolus injection with E coli, as reported elsewhere.

In both groups, a pronounced increase of PAI-1 levels was observed from 2 hours after onset of the challenge and

Fig 2. Fibrinolytic parameters after lethal E coli infusion. Mean ± SEM plasma levels of t-PA (A), PAP complexes (B), and PAI-1 (C) in control (●) and MoAb-treated (○) groups. PAP complexes are expressed as a percentage of NBS-MA-UK. Wilcoxon/Mann-Whitney U test, *P < .05.
on, reaching maximum levels of 3,003 ± 506 and 3,372 ± 780 ng/mL at 6 hours in treatment and control animals, respectively (Fig 2C). A significant difference in the course of PAI-1 levels between groups was noted at 3 hours \( \left( P < .05 \right) \), consistent with a decreased consumption of PAI-1 by t-PA in C6B7-treated animals.

**Neutrophil degranulation.** To study the effect of MoAb C6B7 on neutrophil activation in this experimental model of sepsis, elastase--α1-protease inhibitor complexes were assayed in plasma samples from both groups. Figure 3 shows that anti–factor XII treatment reduced the release of elastase. In control animals, elastase complexes increased during the entire observation period, reaching maximum levels of 1,851 ± 382 ng/mL at 6 hours. This increase was less pronounced in the treatment group, in which peak levels of 913 ± 170 ng/mL were measured. The difference between the course of elastase was significant from 2 hours onward.

**Plasma levels of TNF-α and IL-6.** Plasma levels of TNF-α and IL-6 were assessed in both groups of animals. The course of TNF-α release on lethal challenge was consistent with previous observations⁶⁰ and was not affected by MoAb C6B7: in both groups, a transient and comparable increase in circulating TNF-α was observed, reaching peak levels of 35.4 ± 9.2 and 30.8 ± 4.5 ng/mL at 2 hours in control and treatment groups, respectively (not shown). In contrast, anti–factor XII treatment modestly reduced the appearance of IL-6 (Fig 4). In both groups, administration of E. coli resulted in a progressive increase in circulating IL-6, with identical kinetics during the first 3 hours. Thereafter, levels tended to be reduced in the treatment group, and were significantly different from control levels at 6 hours (181.3 ± 86.4 v 429.2 ± 101.6 ng/mL, \( P < .05 \)).

Observed differences in activation parameters between treatment and control groups potentially might be due to small differences in the number of microorganisms used for the challenge, rather than to the effect of MoAb C6B7. Therefore, we estimated this number, as well as that in blood samples taken 2 hours after the start of infusion in each animal. Table 1 shows that there were no differences between treatment and control groups with respect to the number of CFU in the infusion fluid given to each animal. However, the number of viable bacteria that could be reconstituted from the plasma 2 hours after the challenge was approximately fourfold less in treated compared with control animals. In contrast, endotoxin levels, which reflect the release of lipopolysaccharide (LPS) from circulating bacteria, were not found to be different between the groups (Table 1).

**DISCUSSION**

In a previous study, we have shown that administration of MoAb C6B7, which inhibits activation of factor XII, to baboons that were subsequently challenged with a lethal dose of E. coli was able to reduce factor XII activity by 60%, diminish the decrease in high-molecular-weight kininogen, and prevent the formation of kallikrein–α2-macroglobulin complexes, indicating efficient inhibition of the contact sys-

<table>
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<tr>
<th>CFU (U/mL)</th>
<th>Anti–Factor XII</th>
<th>Control</th>
<th>( P )</th>
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<tr>
<td>Infusion fluid ( \times 10^{06} )</td>
<td>4.27 ± 26</td>
<td>4.87 ± 1.40</td>
<td>.754</td>
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<tr>
<td>2 h ( \times 10^{05} )</td>
<td>1.52 ± 29</td>
<td>6.31 ± 2.59</td>
<td>.009*</td>
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<tr>
<th>Endotoxin (EU/mL)</th>
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<tr>
<td>0 h</td>
<td>2.74 ± 1.91</td>
</tr>
<tr>
<td>1 h</td>
<td>41.36 ± 8.89</td>
</tr>
<tr>
<td>2 h</td>
<td>86.14 ± 11.72</td>
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<tr>
<td>3 h</td>
<td>25.28 ± 6.94</td>
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<tr>
<td>6 h</td>
<td>5.91 ± 1.07</td>
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Mean ± SEM plasma levels of endotoxin before \( t = 0 \) and at 1, 2, 3, and 6 hours after E. coli infusion. Differences between control and MoAb-treated groups were determined by Wilcoxon/Mann-Whitney \( U \) test.

\* \( P < .05 \).
tem. The aim of the present study was to evaluate whether MoAb C6B7–induced reduction of contact activation influenced activation of complement and fibrinolytic cascades, activation of neutrophils, and induction of cytokines.

Complement activation in sepsis is considered to result mainly from direct activation by bacteria and their products. The initial activation of C3 immediately following E coli infusion (Fig 1A) supported the idea of a direct activation by circulating organisms. A number of studies have shown that endotoxin and intact bacteria can activate the complement system directly via the alternative pathway. The observation that C4b/c levels also increased rapidly upon infusion of E coli indicates that at least part of the activation occurred via the classic pathway. In vitro, addition of these E coli bacteria to NBS also results in activation of C3 and C4, indicating that direct contact of the microorganisms and/or their products with blood may induce complement activation via the classic pathway, presumably via IgG and IgM antibodies. However, levels of C3b/c and C4b/c remained elevated and continued to increase, respectively, after E coli infusion had been stopped (Fig 1), suggesting involvement of other activating mechanisms of the complement system, as well. A number of in vitro studies have demonstrated interactions between activated contact proteins and complement factors, although evidence that these interactions also occur in vivo has been lacking. For example, factor XIIa can activate C1 directly by cleavage of the C1r subcomponent. Also, kallikrein can cleave C1 subcomponents, but this results in destruction rather than activation. However, kallikrein can replace factor D in the alternative pathway to generate a C3 convertase by cleaving factor B, and in rabbits kallikrein can generate C5a from C5. Our data imply that inhibition of the contact system reduced complement activation in this experimental model of sepsis. Our observations do not allow definite conclusions with regard to molecular pathways involved in interactions between activated contact proteins and the complement system in baboons. However, the fact that activation of C4 was diminished in treated animals, even during the later stages of the septic process, supports a mechanism involving factor XII–induced activation of C1.

Low doses of endotoxin or TNF have been shown to induce a procoagulant state in human volunteers, resulting from a sustained activation of coagulation, with a more transient activation of fibrinolysis. Similar changes occur in baboons following challenges with lethal or sublethal doses of E coli. In a previous study, we have shown that pretreatment of septic baboons with MoAb C6B7 did not influence the occurrence of disseminated intravascular coagulation, indicating that the contact system does not contribute to coagulation in this model. In contrast, we show here that activation of fibrinolysis was significantly diminished in baboons that received MoAb C6B7, indicating that contact activation had contributed to plasmin formation in untreated animals (Fig 2). A number of in vitro interactions between activated contact factors and the fibrinolytic system have been described. For example, factor XIa, factor Xla, and kallikrein are all capable of directly converting plasminogen to plasmin. However, these reactions are weak and, at plasma concentrations, presumably not significant. However, kallikrein can cleave single-chain u-PA to its active form on cellular surfaces and in a plasmatic environment. Additionally, a factor XII–dependent pathway has been described that involves a u-PA–like plasminogen activator that has been partly characterized. Activation of the contact system may also enhance fibrinolysis through the effects of bradykinin on the release of t-PA from the vessel wall. This latter effect would explain the lower levels of t-PA in baboons that received MoAb C6B7 as compared with untreated controls. In a previous study, we showed that activation of factor XII on administration of desamino d-arginine vasopressin to humans contributes significantly to the induction of plasminogen activator activity and is independent of the release of t-PA. Moreover, angioedema attacks due to a hereditary deficiency of the main inhibitor of the contact system, C1-inhibitor, are associated with concomitant contact activation and plasmin generation. Thus, interactions between the contact and the fibrinolytic system in vivo go beyond the release of t-PA by the endothelium. However, the precise nature of these interactions, as well as their role in sepsis, remain to be established.

Purified plasma kallikrein is able to stimulate neutrophil chemotaxis, aggregation, and oxygen consumption. Furthermore, it also induces these cells to release elastase from their azurophilic granules. Activation of neutrophils in vivo can be assessed by measuring plasma levels of elastase–α1-protease inhibitor complexes. Increased levels of these complexes have been found in human sepsis and were associated with a poor outcome. In this study, circulating elastase–α1-protease inhibitor complexes markedly increased upon infusion of a lethal dose of E coli, which was significantly attenuated by MoAb C6B7 (Fig 3). Although this effect of factor XII blockade may have been mediated indirectly by a decreased liberation of the anaphylatoxins, C3a and C5a, which are potent inducers of neutrophil degranulation in vitro, these data may also reflect a direct agonistic effect of contact proteases on neutrophil activation in this model of sepsis.

Bacterial counts in the infusion fluid used for the challenge were similar for both groups. However, the amount of circulating colony-forming bacteria 2 hours after the start of the infusion was about fourfold less in the treatment group (Table 1). This implies that upon anti–factor XII treatment, E coli must have been cleared more efficiently from the circulation or were killed more rapidly as compared with the control. We are not aware of studies showing an inhibitory effect of contact proteins on the phagocytosis of bacteria; rather, factor XIIa has been shown to downregulate Fcγ,II-Receptor expression on monocytes. Alternatively, an enhanced clearance of E coli organisms in the treatment group may have resulted from the hemodynamic effects of inhibition of the contact system, i.e., a better perfusion of the organs. However, it should be noted that minor alterations inflicted on the outer membrane of bacteria may result in a lack of colony formation, which need not necessarily reflect bacterial death or clearance. Moreover, in contrast to bacterial counts, endotoxin levels were similar for both groups. Thus, whatever mechanism operated to reduce bacterial...
counts more efficiently upon C6B7 treatment, it still resulted in a release of LPS that did not differ from that in untreated control animals. Previous studies in mice have indicated that protection against lethal sepsis is associated with a reduction in serum LPS levels rather than with a reduction in blood bacterial counts. In agreement herewith are observations that in septic patients the presence of biologically active endotoxins is a better harbinger of clinical sepsis than viable bacteria, and correlates with survival. Despite this, our data raised the possibility that some of the observed effects in the treatment group were due to increased clearance rates and/or bacterial killing mechanisms rather than to inhibition of effects of activated contact proteins on other mediator systems. However, this explanation is not supported by the kinetics of TNF-α in both groups, since these were comparable. Furthermore, levels of PAI-1 were not decreased, but were even slightly enhanced in C6B7-treated animals, and the initial increase of IL-6 was similar to that in controls. On the other hand, IL-6 levels during the later stages were modestly reduced in the treatment group. However, this latter observation might support a role for contact proteins in the release of cytokines in vivo, as has been observed in vitro for factor XIIa-induced release of IL-1.

The data presented here demonstrate the complexities of the relationships between blood bacterial numbers, circulating LPS, and inflammatory parameters and the difficulty in establishing their relative roles in experimental infection. In a previous study, we have shown that in this lethal baboon model of sepsis, a protracted decrease in arterial pressure could be attenuated by administration of MoAb C6B7. We concluded that this could be attributed, in part, to a diminished release of bradykinin from high molecular weight kininogen. In addition, as we have shown in the present study, administration of MoAb C6B7 also resulted in attenuation of complement activation, and thus in reduced generation of C3a and C5a. These complement activation products may also have contributed to the observed hemodynamic changes. This explanation is supported by a previous study demonstrating that pretreatment with anti-C5a antibodies in a primate model of sepsis results in a similar recovery in mean arterial pressure.

In conclusion, we demonstrated that administration of a neutralizing MoAb against factor XII to baboons suffering from lethal sepsis is accompanied by a decreased activation of complement and fibrinolytic systems and a reduced release of IL-6 and neutrophil elastase. Our findings suggest that in this animal model, activated contact proteins may contribute to the activation of other inflammatory mediators, and once more illustrate the complexity of mechanisms involved in the pathogenesis of sepsis.

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Inhibition of factor XII in septic baboons attenuates the activation of complement and fibrinolytic systems and reduces the release of interleukin-6 and neutrophil elastase

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