Effect of Active Site-Modified Thrombin on the Hydrolysis of Platelet-Associated Glycoprotein V by Native Thrombin

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To determine the relationship between equilibrium binding of thrombin to sites on the platelet surface and the cleavage of membrane glycoprotein V (GPV) by thrombin, we examined the effect of active site-modified thrombin (1-chloro-3-tosylamido-7-amino-1-2-heptanone thrombin toslysCH₂-thrombin) on the binding of native thrombin to platelets and on the hydrolysis of GPV by native thrombin. ToslysCH₂-thrombin inhibited binding of native thrombin to high affinity sites on the platelet surface. In contrast, hydrolysis of GPV by native thrombin, even at threshold thrombin concentrations, was not inhibited by pretreatment with toslysCH₂-thrombin at concentrations up to 210 nmol/L. ToslysCH₂-thrombin also had no appreciable effect on platelet aggregation or release of ¹⁴C-serotonin induced by native thrombin. Because toslysCH₂-thrombin does not inhibit platelet release, aggregation, or GPV hydrolysis by native thrombin but does inhibit high affinity surface binding by native thrombin, these results indicate that thrombin binding and hydrolysis of GPV are separate and unrelated events.

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MATERIALS AND METHODS

Materials

Vibrio cholerae neuraminidase, 500 U/mL, was purchased from Schwarz/Mann, Cambridge, Mass. Galactose oxidase was obtained from United States Biochemical Corp., Cleveland, and was purified and assayed for activity by the method of Hatton and Regoeczi.¹² Tritiated sodium borohydride (NaBH₄), 5 to 15 Ci/mmol was purchased from Research Products International (Mt Prospect, Ill)

*The nomenclature used in this article is based upon that of Phillips and Agin.¹⁰ Others have used a nomenclature based on Mr by PAGE,¹¹ ie, GPV is termed GP 80,000.
in 5-mCi vials and dissolved in 0.001 mol/L NaOH on the day of use. Serotonin labeled with $^{14}$C, 40 mCi/nmol, and Aquasol 2 were from New England Nuclear, Boston. Sodium dodecyl sulfate (NaDdSO$_4$, 99.0% pure), 2-mercaptoethanol and glycerol were products of British Drug House and were purchased from Gallard-Schleisinger, Carle Place, NY. Electrophoresis grade polyacrylamide, bis N,N'-methylene acrylamide, ammonium persulfate, Coomassie Brilliant Blue R-250, high molecular weight (mol wt) NaDdSO$_4$-polyacrylamide gel electrophoresis (PAGE) standards and Enzymobeads were obtained from Bio-Rad Laboratories, Rockville Centre, NY. Enzymobeads were prepared as recommended by the manufacturer and used within two weeks of reconstitution. N,N',N'-tetramethylenediamine (TEMED) and X-Omat XAR-5 film were from Eastman Kodak Company. 1-Chloro-3-tosylamido-7-amino-1,2-heptanone (toslySCH$_2$Cl) was obtained from VEGA, Tucson. Bovine fibrinogen (Pentex, 70% clottable) and bovine albumin (Pentex, fatty acid free, Fraction V) were obtained from Miles Laboratories, Bedford, Mass. Millipore filters (RAPW-025-00) were obtained from Millipore Corporation and silicone oils were from William F. Nye, Inc, New Bedford, Mass. Iodo-beads were from Pierce Chemical Company, Rockford, Ill. $^{125}$I, carrier free, as sodium $[^{125}I]$-iodide was purchased from Amersham Corp., Arlington Heights, Ill. All other chemicals were of reagent grade or better.

**Methods**

**Thrombin iodination and chemical modification.** Purified human α-thrombin prepared as previously described was kindly provided by Dr. R. L. Lundblad (Chapel Hill, NC). Purified human α-thrombin in 0.05 mol/L sodium phosphate, pH 7.0, was radioiodinated, using either Enzymobeads or lodobeads as recommended by the supplier. Following iodination, thrombin was dialyzed against 0.05 mol/L sodium phosphate, pH 8.0. The radiolabeled thrombin had a specific activity of 115,000 to 180,000 cpm per unit and retained greater than 95% clotting activity after the iodination and dialysis procedures.

Thrombin was modified with toslySCH$_2$Cl according to the method of Glover and Shaw except that $10^{-4}$ mol/L toslySCH$_2$Cl in 0.05 mol/L sodium phosphate, pH 8.0, was incubated with thrombin for two hours at room temperature followed by 24 hours at 4°C. The toslySCH$_2$-thrombin was then extensively dialyzed at 4°C for 24 hours against Ca$^{2+}$-free Tyrode’s solution, pH 7.4, to remove residual toslySCH$_2$Cl. Protein determination was made by the ninhydrin method of Lowry and modified by the method of Siegel. Autoradiographs were scanned with a Zeinich Soft laser scanning densitometer using a tungsten light source, and areas under the peaks were determined to quantitate the radiolabeled bands. The GPV$_n$ glyocalcin ratio in the supernatant provided the best quantitative measure of GPV hydrolysis for each individual experiment, normalizing any variations in protein concentration on a given gel.

**Platelet preparation.** Platelets were obtained from normal healthy donors who denied recent alcohol or aspirin ingestion, as approved by the Committee on the Protection of the Rights of Human Subjects, School of Medicine, University of North Carolina at Chapel Hill. Six parts of venous blood were collected into plastic syringes containing one part acid–citrate–dextrose, pH 6.8. Platelet-rich plasma (PRP) was prepared by centrifugation of the anticoagulated blood at 100 × g for 20 minutes at room temperature. For studies of platelet aggregation, the PRP was incubated with $^{3}$H-serotonin (0.1 μCi/mL of platelet rich plasma) at 37°C for 30 minutes and gel-filtered in a plastic column of Sepharose CL-2B equilibrated with Ca$^{2+}$-free Tyrode’s solution. For the competition studies, platelets were preincubated with toslySCH$_2$-thrombin at final concentrations between 2.1 and 210 nmol/L for three minutes before native thrombin was added. In other studies, toslySCH$_2$-thrombin was held constant at 210 nmol/L and the concentration of native thrombin was varied.

**RESULTS**

**Binding Studies**

Iodo-$[^{125}I]$-thrombin and iodo-$[^{125}I]$-toslysCH$_2$-thrombin 1125 bound to gel-filtered platelets in a similar fashion. Binding was biphasic, demonstrating both high and low affinities. Using Scatchard analysis, the number of binding sites and dissociation constants were similar for both radiolabeled thrombins. Iodo-$[^{125}I]$-thrombin and iodo-$[^{125}I]$-toslysCH$_2$-thrombin also bound to gel-filtered platelets that had been treated with neuraminidase, galactose oxidase, and cold NaBH$_4$. Binding was qualitatively similar to that to unmodified platelets, but the total binding and number of binding sites were reduced as compared to the unmodified platelets.
Fig 1. Binding of iodo-[125I]-thrombin to neuraminidase-galactose oxidase-Neu NaBH₄-treated platelets and competition by toslyCH₂-thrombin thrombin. Binding of iodo-[125I]-thrombin to gel-filtered platelets (250 µL at 6.0 × 10⁵/mL) treated with neuraminidase, galactose oxidase, and NaBH₄ and suspended in Ca²⁺-free Tyrode solution containing 10 mg/mL fatty acid free bovine serum albumin was determined as described in Materials and Methods in the presence and absence of 370 nmol/L toslyCH₂-thrombin. Thrombin bound (T₁) is plotted as a function of the concentration of thrombin added (TT) for the lowest thrombin concentrations to illustrate high-affinity binding. (Inset) Expanded scale showing T₁ vs. TT at higher thrombin concentrations. Binding of iodo-[125I]-thrombin to platelets (solid circle); binding of iodo-[125I]-thrombin in the presence of toslyCH₂-thrombin (open circle). The results are representative of two experiments.

When neuraminidase-, galactose oxidase-, and NaBH₄-treated platelets were pretreated with unlabeled toslyCH₂-thrombin and then incubated with serial dilutions of iodo-[125I]-thrombin, there was inhibition of high-affinity binding of iodo-[125I]-thrombin as compared to the control platelets that had not been pretreated with toslyCH₂-thrombin (Fig 1, Table 1).

GPV Hydrolysis

Intact tritium-labeled platelets in buffer containing EDTA were treated with native thrombin for three minutes and centrifuged; the platelet pellet and corresponding supernatant fractions were analyzed by NaDodSO₄-PAGE under reducing conditions. Gels stained for protein showed several changes in the samples treated with native thrombin. There was disappearance from the platelet pellet of bands corresponding to thrombospondin (Mr 190,000) and the α-chain (Mr 67,000), β-chain (Mr 55,000), and γ-chain (Mr 50,000) of fibrinogen on reduced gels, and the appearance in the supernatant fractions of bands with identical mol wt. In addition, at higher thrombin concentrations, a 92,000 Mr band was seen in reaction supernatants that migrated in the region of the γ-γ dimer of fibrin.

Autoradiograms of the tritium-labeled thrombin-treated platelets compared with those of controls showed decreased radioactivity associated with GPV (Mr 69,000). The supernatant fraction from the thrombin-treated platelets showed increased radioactivity in GPV₁₁ (Mr 58,000). In addition, both control and thrombin-treated supernatants contained radiolabeled bands that corresponded to glycolocalcin (GC) and GPV. The amounts of these two proteins varied somewhat from experiment to experiment, usually in association with the platelet counts of the reaction mixtures. However, for a given experiment, the areas of each of these bands in the supernatants remained nearly constant for three-minute incubation periods, based on the densitometric tracings of the autoradiographs, except at higher thrombin concentrations in which soluble GPV was hydrolyzed.

At three minutes, the amount of GPV₁₁ in the supernatant correlated with thrombin concentration. Supernatant GPV₁₁ was maximal at thrombin concentrations of 10 nmol/L or greater, whereas at lower thrombin concentrations less GPV₁₁ was liberated (Table 2).

ToslyCH₂-thrombin did not hydrolyze platelet-associated GPV or result in the appearance of the hydrolytic product, even at concentrations as high as 210 nmol/L (Fig 2, lane 2). Neither was there any release of thrombospondin or fibrinogen.

When labeled, gel-filtered platelets were incubated with toslyCH₂-thrombin at concentrations between 2.1 and 210 nmol/L for three minutes followed by native thrombin at a concentration of 21 nmol/L, equivalent amounts of GPV₁₁ were present in each of the supernatants and were identical to the amount of

Table 1. Effect of TosLysCH₂-Thrombin on Binding of Native Thrombin to NGB-Treated Platelets

<table>
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<th>Low Affinity</th>
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<td>6.50 × 10⁴</td>
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Washed platelets treated with neuraminidase, galactose oxidase, and borohydride (NGB) were pretreated with buffer (Ila samples) or toslyCH₂-thrombin (Ila/toslyCH₂-Ilia samples), then incubated with different concentrations of native thrombin as described in Materials and Methods. The numbers of binding sites per platelet and association constants (Kₐ) were calculated from Scatchard plots of the binding data in Fig 1.
GPV in a sample pretreated with buffer (Fig 2). When the concentration of toslysCH2-thrombin was held constant at 210 nmol/L, and native thrombin was added at concentrations of 2.1 nmol/L, 5.2 nmol/L, and 10.5 nmol/L for three minutes, GPV appeared in the supernatant samples in proportion to the concentration of native thrombin and was similar to the amount of GPV that appeared in supernatant samples that had been pretreated with buffer for three minutes, followed by native thrombin at the same concentrations (Table 2).

At all concentrations of native thrombin that hydrolyzed GPV, thrombospondin and fibrinogen were increased in the supernatants. There was no difference between the samples that were pretreated with toslysCH2-thrombin and those samples pretreated with buffer.

**Platelet Release and Aggregation Studies**

Native thrombin induced the release of 14C-serotonin at concentrations from 0.42 to 210 nmol/L, with 50% release occurring at 1.5 to 3.5 nmol/L (range of two experiments). ToslysCH2-thrombin, in concentrations from 2.1 to 210 nmol/L, did not induce 14C-serotonin release from gel-filtered platelets. When gel-filtered platelets were pretreated for three minutes with concentrations of toslysCH2-thrombin ranging from 4.2 to 210 nmol/L, followed by native thrombin at various concentrations for three minutes, the 14C-serotonin release curves were no different from those of platelets which had been pretreated with buffer.

Platelet aggregation results were similar to the 14C-serotonin release results. Native thrombin produced aggregation with threshold concentrations of 0.42 to 2.1 nmol/L (range of two experiments). Maximal aggregation occurred at 2.1 to 4.2 nmol/L. Pretreatment with toslysCH2-thrombin did not alter the aggregation response of platelets to native thrombin, even with toslysCH2-thrombin concentrations of 210 nmol/L.

**DISCUSSION**

Previous studies have shown specific binding of native thrombin to the surface of human platelets and have demonstrated two classes of binding sites. Thrombin modified at the enzyme active site binds to platelets in a similar fashion and competes with native thrombin for these binding sites, suggesting that active site-modified thrombin and native thrombin bind to the same sites on platelet surfaces. Thrombin modified at the active site also inhibits membrane depolarization in response to native thrombin. In contrast, active site-modified thrombin does not compete with native thrombin for thrombin-induced platelet activation and in some instances potentiates the action of native thrombin. The present study confirms these observations and extends the competition studies to the hydrolysis of GPV, showing that the...
hydrolysis of platelet-associated GPV by native thrombin is not inhibited by active site-modified thrombin, whereas binding is inhibited under similar conditions. Because cleavage of GPV was not inhibited under conditions in which binding was inhibited, these data suggest that high-affinity binding of thrombin to platelets and hydrolysis of surface-associated GPV are separate and unrelated events. Thus, binding does not appear to orient the thrombin molecule for the cleavage of GPV.

Although hydrolysis of GPV by thrombin does not appear to occur through currently defined binding sites, the role that GPV cleavage plays in platelet activation by thrombin is still uncertain. Several observations are consistent with the hypothesis that cleavage and activation are related. First, GPV is the only surface substrate for thrombin reproducibly identified by currently used labeling procedures.10,11,23,24 Second, GPV is cleaved and GPVβ is generated by other thrombin-like proteases that activate platelets, but not by proteases that do not activate platelets.25 Third, platelets from patients with Bernard-Soulier syndrome, which have no detectable surface-oriented GPV,26,27 demonstrate an abnormal response to thrombin, although this reduced responsiveness could be related to the absence of glycoprotein Ib (GPIb)28 rather than to the absence of GPV. Fourth, dose-response studies indicate a close relationship between platelet activation and GPV hydrolysis by thrombin.11 Last, the results of the competition studies presented here further demonstrate a close parallel between platelet activation and GPV hydrolysis. However, recent studies have shown that this relationship is more complex than was initially conceived. McGowan and co-workers have shown that partial removal of GPV from the surface of platelets with chymotrypsin or platelet calcium-activated protease reduced the rate of thrombin-catalyzed hydrolysis of the remaining surface-associated GPV but had little effect on the extent of platelet activation.23,29 They further showed that when GPV was partially removed from PGI2-desensitized platelets by thrombin, the resulting platelets were desensitized to subsequent activation by thrombin, but showed normal hydrolysis of the remaining GPV. They have therefore been able at least to dissociate GPV hydrolysis partially from platelet activation and vice versa. Furthermore, unless it is liberated from the platelet surface by some other protease during platelet preparation, GPV appears to be a peripherally located membrane protein,30 and it is difficult to envision a critical role for such a loosely associated protein.

In summary, the molecular events relating to the activation of platelets by thrombin are complicated, and the precise relationship between thrombin binding, cleavage of GPV, and cell activation are uncertain. Although the results of this study indicate that high-affinity thrombin binding and GPV cleavage by thrombin are unrelated events, GPV remains the only substrate for thrombin that has been identified on the platelet surface. Further studies are required to determine how GPV functions in platelet activation.

ACKNOWLEDGMENT

We gratefully acknowledge the technical assistance of John Huffman, Yvonne Monroe, and Jane Boriack and express our great appreciation to Dr RL. Lundblad for his suggestions and comments concerning these studies. We also thank Ms Renee B. Williams for excellent secretarial assistance.

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Effect of active site-modified thrombin on the hydrolysis of platelet-associated glycoprotein V by native thrombin

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