The Anticoagulant Mechanism of Action of Heparin in Contact-Activated Plasma: Inhibition of Factor X Activation

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The effects of heparin on the activation of blood coagulation factors IX and X in contact-activated plasma were determined in the present study. In the presence and absence of 0.5 U/mL heparin, the amounts of factor IX that were cleaved 30 minutes after the addition of calcium and phospholipid to plasma exposed to glass (ie, contact activated) were essentially identical. In the absence of heparin, however, the plasma clotting time was between three and four minutes, while in the presence of heparin, the clotting time was approximately 40 minutes. More factor IXa was inhibited by antithrombin III in the presence of heparin than in its absence, but factor IXa levels sufficient for factor X activation appeared to be present in the heparinized plasma. Neither an increase in factor Xa nor a decrease in factor X was detected, however, in heparinized plasma. We conclude that the step in the intrinsic pathway of coagulation that is inhibited in the presence of heparin is at the level of factor X activation.

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STUDIES REPORTED over 45 years ago indicated that a plasma component is required for the anticoagulant activity of heparin. The plasma component, originally termed heparin cofactor and referred to now as antithrombin III, has since been isolated and shown to be an effective inhibitor of thrombin both in the presence and absence of heparin. The rates of thrombin inhibition by antithrombin III, however, are three to four orders of magnitude faster in the presence of heparin than in its absence. Heparin has also been shown to increase the rates of inhibition (by antithrombin III) of most of the enzymes (serine proteases) that are formed during the process of blood coagulation. These observations have led to the conclusion that the general anticoagulant mechanism of action of heparin is directly related to accelerated rates of inhibition of the blood coagulation enzymes by antithrombin III. In vitro studies, wherein the heparin-accelerated rates of inhibition of purified (blood coagulation) enzymes by antithrombin III have been clearly demonstrated, do not provide sufficient information to derive a detailed description of the anticoagulant mechanism of action of heparin. The process of blood coagulation proceeds via relatively well-defined pathways (intrinsinc, extrinsic) in which the various coagulation factors (zymogens, cofactors) are sequentially activated. Several steps in these pathways involve zymogen activation by a surface (eg, phospholipid, platelet)-bound enzyme. In addition, maximal rates of zymogen activation are not attained until specific protein cofactors are activated and surface-bound enzyme–cofactor complexes are formed. To obtain a more specific description of the anticoagulant mechanism of action of heparin, the effects of enzyme–cofactor–phospholipid complex formation on the heparin-accelerated antithrombin III-enzyme reaction rates must be determined.

In the present report, we describe experiments that were conducted to determine the step in the intrinsic pathway of plasma coagulation that is blocked in the presence of heparin. Our experimental approach was based on the assumption that contact activation of plasma (ie, exposure of plasma to a glass surface) containing calcium and a phospholipid source would lead to the sequential activation of the coagulation factors of the intrinsic pathway and that factor activation would not be detected in any step in the pathway subsequent to the step that is blocked in the presence of heparin. Our results suggest that steps preceding factor X activation are not significantly affected in the presence of heparin, but the rate of factor X activation is decreased to essentially undetectable levels.

MATERIALS AND METHODS

Materials

N'-p-tosyl-glycyl-t-prolyl-t-arginine-p-nitroanilide (TosGly-ProArgNaN, Chromozyme TH) was purchased from Boehringer Mannheim, Indianapolis. N-benzoyl-L-isoleucyl-L-glutamyl-glycyl-arginine-p-nitroanilide (S-2222) was purchased from Helena Laboratories, Beaumont, Tex. Factor IX-deficient plasma (<1% factor IX antigen) was a gift from the Clinical Coagulation Laboratory, North Carolina Memorial Hospital, Chapel Hill, NC. Porcine mucusal heparin (165 USP U/mg), which was essentially devoid of protein, was generously provided by Dr G. van Dedem and E. Coyne, Diosynth B.V., Oss, The Netherlands. 1,5-Dimethyl-1,5-diazaundecamethylene polybromide (polybromine) was purchased from Aldrich Chemical Co, Inc, Milwaukee. Russell's viper venom (RVV) and ovalbumin were purchased from Sigma Chemical Co, St Louis. Iodobeads were purchased from Pierce Chemical Co, Rockford, Ill. BioGel P-6 (200 to 400 mesh) was purchased from BioRad Labora-
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Cleavage in Contact-Activated Plasma

Measurement of Activated Factor IX in Contact-Activated Plasma

Measurement of Activated Factor X in Contact-Activated Plasma
The amount of unactivated factor X in a given sample was also determined. Samples (20 μL) taken at timed intervals were added to a solution (0.21 mL) containing 0.05 mol/L TRIS HCl (pH 7.4), 0.23 mol/L NaCl, and 0.30 mg/mL polybrene and incubated at 37 °C for four minutes. A solution (0.04 mL) containing unfractionated-RVV (A250 = 0.50), and 20 mmol/L calcium chloride was then added, and the mixture incubated for one minute. The amidolytic activity of the solution was determined as described above for the measurement of factor Xa. Factor X concentrations were expressed as a percentage of the factor X concentration in normal plasma.

RESULTS

Factor IX Activation in Contact-Activated Plasma

The amounts of radiolabeled factor IX cleaved in contact-activated plasma were similar in the presence and absence of heparin. As shown in Fig 1, approximately 40% of the radiolabeled factor IX added to factor IX-deficient plasma appeared to be cleaved to factor IXαβ, as indicated by the appearance of radiolabeled heavy and light chains, after incubation for 30 minutes in the presence and absence of heparin. In the absence of heparin, the plasma clotting time was approximately 3½ minutes. Samples taken immediately before and after clotting indicated that approximately 2% of the radiolabeled factor IX was activated at the time of clotting (data not shown), as has been reported previously.15 The amount of radiolabeled factor IX cleaved in the absence of heparin increased with time after clotting occurred to reach the level indicated in Fig 1. While the plasma clotting time in the presence of heparin was around 40 minutes, the amount of radiolabeled factor IX that was cleaved increased at about the same rate as was observed in the absence of heparin.

There was no evidence for the formation of a complex between antithrombin III and the radiolabeled factor IXa in the data shown in Fig 1. The stability of the antithrombin III–factor IXa complex to the conditions of SDS-PAGE was dependent, however, on the gel system used. The results shown in Fig 2A, in which samples were run (unreduced) according to the method described by Weber and Osborn,14 indicated that a small (~5%) amount of radiolabeled factor IXa appeared to be complexed with antithrombin III in...
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plasma activated in the absence of heparin. In the presence of heparin, approximately 40% of the radiolabeled factor IXa appeared to be complexed with antithrombin III after 15 minutes of incubation. After incubation for 30 minutes, approximately 60% of the radiolabeled factor IXa was complexed with antithrombin III. These results, shown in Fig 2B, indicated that approximately 40% of the radiolabeled factor IXa, which corresponded to 16% of the total radiolabeled factor IX added to the plasma, was uncomplexed after incubation for 30 minutes in the presence of heparin. In a parallel experiment, the amount of activated factor IX, detected by activity, increased as a function of incubation time. These results, shown in Fig 3, indicated that ~14% of the total factor IX in plasma was detectable as activated factor IX after incubation for 30 minutes.

Factor X Activation in Contact-Activated Plasma

In the presence of heparin, there was neither a measurable increase in factor Xa nor a decrease in the total factor X present in contact-activated plasma. These results are shown in Fig 4. In the absence of heparin, approximately 1% of the factor X present in plasma appeared to be activated immediately after clotting. Factor X activation and inhibition continued after clotting had occurred, as indicated by the transient increase in factor Xa and subsequent decreases in both factor Xa and the total amount of factor X present. These results are also shown in Fig 4.

DISCUSSION

The generalized anticoagulant mechanism of action of heparin can be attributed to the rate-accelerating effect of heparin on the reactions between antithrombin III and the enzymes that are formed during the process of blood coagulation. Under any set of conditions, the rates at which the steps in the coagulation pathways proceed will be decreased according to the extent to which the various enzymes are inhibited by antithrombin III. In the presence of heparin, a given step in the pathway can be essentially blocked if the rate of zymogen activation (enzyme formation) is much less than the antithrombin III–enzyme reaction rate. Even when the rate of zymogen activation exceeds the antithrombin III–enzyme reaction rate in the presence of heparin, partial inhibition of the enzyme as it is formed will decrease the rates of zymogen activation in subsequent steps in the pathway. In this way, the anticoagulant mechanism of action of heparin could be attributed to a cumulative effect of heparin accelerated–antithrombin III–enzyme reactions throughout the coagulation pathways.

For several reasons, it has been difficult to describe the anticoagulant mechanism of action of heparin in more specific terms. It cannot be assumed that all of the heparin-accelerated antithrombin III–enzyme reactions, which have been demonstrated using purified proteins, take place in plasma. Scott and co-workers have shown, for example, that the antithrombin III–factor XIa reaction is not accelerated by heparin in plasma. The experimental conditions under which the anticoagulant effects of heparin are studied determines, in part, the anticoagulant mechanism of action of heparin that is observed. For example, activation of coagulation by the addition of factor Xa to plasma containing calcium and phospholipid is useful in determining the anticoagulant mechanism of action of heparin with respect to the final steps in the
coagulation pathway(s), but the anticoagulant effects of heparin in any of the steps preceding factor Xa formation are not detected. Perhaps the most critical experimental condition to be considered is the heparin concentration. In view of the potential cumulative anticoagulant effects of heparin, a given step in the coagulation pathway could be completely blocked in the presence of high heparin concentration, but only partially inhibited when the heparin concentration is decreased. The apparent anticoagulant mechanism of action of heparin, therefore, could be altered by simply changing the heparin concentration.

Our objective in the present study was to obtain a more detailed description of the anticoagulant mechanism of action of heparin in a relatively well-defined plasma system. We were specifically interested in determining the step in the intrinsic pathway of coagulation that would be inhibited or blocked in the presence of reasonable levels of heparin. Under the experimental conditions used in the present study, the results indicate that the step in the intrinsic pathway that is essentially blocked in the presence of heparin (0.5 U/mL) is at the level of factor X activation.

Although evidence was obtained indicating that activated factor IX is inhibited, by complex formation with antithrombin III, to a greater extent in heparinized plasma (Fig 2), significantly higher levels of factor IXa were present in the heparinized plasma than were required for factor X activation (and coagulation) to occur in the absence of heparin. Factor IXa levels corresponding to approximately 5% of the total factor IX in plasma were found in heparinized plasma five minutes after contact activation (Fig 3), whereas only 2% of the total factor IX was activated at the time of clotting (~3½ minutes) in the absence of heparin. These results suggest that a "cumulative" anticoagulant mechanism of action of heparin is not likely in the experimental system we have studied. Specifically, heparin does not appear to have had a significant effect on the reaction rates between antithrombin III and the enzymes preceding factor Xa in the intrinsic pathway (ie, factors XIIa, Xla, IXa, and kallikrein).21-24

The specific anticoagulant mechanism of action of heparin in the plasma system we have studied appears to involve inhibition of a step in the intrinsic pathway subsequent to factor IX activation, which is also independent from factor IXa inhibition by antithrombin III. Although we did not detect significant factor X activation in heparinized plasma during the 30-minute incubation time period studied (Fig 4), it is possible that trace amounts of factor Xa were formed. The factor X activation rate, however, must have been much slower in the presence of heparin than in its absence. Approximately 30% of the factor X present in plasma was activated in 30 minutes in the absence of heparin, whereas there appeared to be no decrease in the factor X level in the presence of heparin. These results suggest that the step in the intrinsic pathway that is inhibited in the presence of heparin is essential for "physiological" rates of factor X activation to be attained. Trace amounts of factor Xa appear to be required for factor VIII activation,10,21 and factor VIII activation is required for rapid rates of factor X activation by factor IXa to be attained. Thus, it is possible that the specific step in the intrinsic pathway that is inhibited in the experimental system we have studied is the activation of factor VIII by factor Xa. Ofosu and co-workers22 have reported studies that indicate that heparin, in the absence of antithrombin III, reversibly inhibits factor VIII activation by factor Xa. In the presence of antithrombin III, the rate-enhancing effect of heparin on factor Xa inhibition (by antithrombin III) could further decrease the "feedback" activation of factor VIII and effectively block the intrinsic pathway at the level of factor X activation. However, since heparin may also affect the protein-protein and protein-phospholipid interactions involved in the assembly of the "tenase" complex, further investigation is required to identify the specific mechanism of inhibition of factor X activation by heparin-antithrombin III observed in the present study.

The anticoagulant mechanism of action of heparin under any set of in vitro experimental conditions must be rigorously defined if meaningful conclusions are to be reached with respect to the antihemostatic and antithrombotic effects of heparin in vivo. In particular, it is very important that a given assay procedure used in monitoring heparin therapy is understood in terms of the specific anticoagulant mechanism of action of heparin that is reflected by the assay results. Through careful evaluation of well-defined test results and clinical observation, the properties of heparin that correlate with in vivo function might then be determined. In view of recent efforts to obtain safer preparations of heparin for therapeutic use, it is important to establish the correlation between in vitro and in vivo effects of heparin.

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