Early Events in the Plasmin Digestion of Fibrinogen and Fibrin

EFFECTS OF PLASMIN ON FIBRIN POLYMERIZATION*

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We have studied the effects of limited plasmin digestion of fibrinogen and fibrin on the physical properties of fibrin gels. After limited digestion the rigidity (elasticity) of the clot formed from degraded fibrinogen is 1% of the rigidity obtained from undegraded fibrinogen, whereas the decrease in clottability as a result of this limited digestion is only about 10%. When plasmin digests fibrin in gel form, the degradation process is significantly prolonged; the rigidity of the attacked gel increases and remains high (hyper-rigidity) for 2 to 4 h and then disappears relatively abruptly. Plasmin cleaves the α (or Aα) chain and releases the hydrophilic, COOH-terminal portion (M₆ = 44,000). Plasmin apparently has a high affinity for a site about one-third of the way from the NH₂ terminus of the α chain of fibrin; plasmin also prefers fibrin to fibrinogen as a substrate in a system where both species are present in equal amounts. The high affinity for the first site of lysis causes the digestion of fibrin to be orderly, in the sense that in the first phase of digestion only α chains are split, and the rigidity of the gel does not fall. The low rigidity of a fibrin gel formed from fibrinogen digested briefly with plasmin has been reproduced in a fibrin gel prepared by first briefly digesting fibrin with plasmin, then dissolving this material in NaBr, and finally allowing the fibrin to gel again. Fibrin molecules lacking the COOH-terminal two-thirds of the α chain form an abnormal network of fibrin fibers of low rigidity, whereas the normal fibrin network does not lose its rigidity when these same peptides are removed.

It is suggested that the hydrophilic COOH-terminal two-thirds of the α chain serves to maintain a fibrin polymerization site in the adjacent portion of the NH₂-terminal part of this chain exposed on the surface of the fibrin molecule.

The mechanism of plasmin digestion of fibrinogen has been studied extensively in recent years (for reviews, see Refs. 1 and 2). Most investigations have emphasized changes in the subunit structure of fibrinogen during the course of plasmin digestion, which ultimately produced the terminal products, D and E. Some studies have dealt with the advanced stage of degradation of these end products, and others have dealt with the early stage of digestion in which fibrinogen is degraded to species that still possess about 87% of the original clottability (3–7). The plasmin degradation of bovine fibrinogen and non-cross-linked fibrin in solution and in gel form has been studied by Inoue et al. (8). They found that fibrinogen and fibrin monomer in solution are degraded in a similar manner; the degradation of fibrin gel follows a different pattern, in which the β chains of fibrin in the gel remain intact longer in the early stage of digestion.

We have investigated the plasmin degradation process by measuring changes in the clot rigidity with a sensitive elastometer. This study focused on the structural changes that occur in fibrinogen and fibrin gels in the early stage of plasmin digestion, during which the loss of clottability is about 10%. The observed differences in the physical changes in fibrinogen and fibrin have been correlated with changes in the subunit structure caused by fibrinolysis.

EXPERIMENTAL PROCEDURES

Materials — Human fibrinogen (grade L, 94% clottable) was purchased from A. B. Kabi (Stockholm, Sweden). This preparation contained trace amounts of Factor XIII. Bovine thrombin was obtained from Parke-Davis. Plasmin in 50% glycerol (Michigan Department of Public Health Lot ERD 166) contained 55 casein units/ml. Lyophilized plasmin (A. B. Kabi Lot 30323) contained approximately 18 casein units/mg of protein and was dissolved in 50% glycerol and stored at −25°C. Trypsin inhibitor (Trasylol, aprotinin; FIA Pharmaceuticals) contained 10,000 KIU/ml. Ancrod (Venacil, Lot 09-006-DH) was a gift from Abbott Laboratories. Fibrinogen and thrombin stock solutions were prepared as previously described (9).

The intactness of the fibrinogen was monitored by SDS-polyacrylamide gel electrophoresis. Fibrin monomer was prepared as described by Donnelly et al. (10) and modified by Lorand and Ong (11). The clottability of the fibrin monomer was 96%. Fibrinogen, Fraction I-8 (12), was kindly given to us by Dr. M. W. Mosesson (SUNY Downstate Medical Center).

Measurements — The method used for the rigidity measurements has been described (15). The degradation of fibrin, as followed by rigidity measurements, can be performed by simultaneously adding a relatively large amount of thrombin and a varying amount of plasmin to the fibrinogen solution to make the clotting time of the fibrinogen solution approximately 20 s and to vary the dissolution

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© The abbreviations used are: KIU, kallikrein inhibitor unit; SDS, sodium dodecylsulfate.
Limited Plasmin Digestion of Fibrin: Role in Polymerization

The mechanical strength of the fibrin gel reaches 90% of its normal under the action of a small amount of plasmin. With increasing concentrations of plasmin, the hyper-rigidity effect diminishes and eventually is lost. The absolute concentration of fibrin is also important, as well as the plasmin/fibrin ratio. This specific effect was observed at a fibrin concentration of about 0.6 mg/ml but not at a higher fibrin concentration or at a higher pH and ionic strength. However, hyper-rigidity was observed under conditions that did not lead to covalent cross-linking, that is, at a low calcium concentration or when ancador was used instead of thrombin but again only at a low fibrinogen concentration. This indicates that the development of hyper-rigidity is not an effect of the covalent cross-linking of α chains by Factor XIIIa, which is known to increase clot rigidity (9, 15). Turbidity measurements did not show any difference between the gel that developed hyper-rigidity and the control gel throughout the entire clotting period, indicating that the observed hyper-rigidity is not due to a change in the thickness of the fibrin fibers making up the network.

Changes in the Structure of Fibrinogen and Fibrin duringFig. 1. Time dependence of the rigidity of fibrin gels formed by adding thrombin to fibrinogen solutions. A varying amount of plasmin was added at the same time as the thrombin. Fibrinogen, 1.3 mg/ml; thrombin, 1.5 NIH units/ml; 0.1 M NaCl, 0.05 M Tris (pH 7.4); 1.15 x 10⁻⁴ M CaCl₂; 37°. The plasmin concentration in casein units/mg of fibrinogen is indicated by each curve.

Fig. 2. Same as for Fig. 1. Fibrinogen, 0.6 mg/ml; thrombin, 0.6 NIH unit/ml; 25°.
Limited Plasmin Digestion: Gel Electrophoresis—Plasmic digestion of fibrinogen and gelled fibrin was further characterized by analyses of the time dependence of the changes in subunit structure with SDS-polyacrylamide gel electrophoresis. The conditions were chosen so that hyper-rigidity could best be observed. Figs. 4 and 5 show the results of gel electrophoretic analyses designed to follow changes in the subunit structure of fibrinogen and fibrin gel at different stages of plasmic digestion. The scans correspond to approximately 82% clottability. The gels for fibrinogen show the disappearance of \( \alpha \) chain in about 65 min with the concomitant appearance of a band with a molecular weight of 29,000. The set for fibrin of Fig. 4 shows considerable \( \gamma \gamma \) dimer formation, which results from the action of contaminating Factor XIII in the presence of calcium ion. The band corresponding to \( \alpha \) chain disappears almost completely after 35 min of reaction, while bands with molecular weights of 44,000 and 26,000 appear and increase. Similar results were obtained when anced was used instead of thrombin (Fig. 5). The gels of anced fibrin still show a small degree of \( \gamma \gamma \) dimerization, which is probably due to activation of Factor XIII by an impurity in the anced preparation.

In agreement with others (16, 17), we conclude that the bands with molecular weights of 30,000 and 26,000 contain the NH\(_2\)-terminal portions of the \( \alpha \) and \( \alpha \) chain, respectively. These NH\(_2\)-terminal portions of the \( \alpha \) chains are attached to other parts of the fibrinogen molecule via disulfide cross-links. The other, COOH-terminal portion of the \( \alpha \) chain is not covalently attached to other chains, at least until \( \alpha \) chain cross-links are introduced by Factor XIIIa. Although the identity of the band with a molecular weight of 44,000 cannot be deduced with certainty, other data, reported in the next section, support the interpretation that it contains the COOH-terminal part of the \( \alpha \) chain. There is no evidence for \( \beta \) chain degradation in these early digests, and therefore there is no reason to assume that this band contains a \( \beta \) chain fragment. This band was also observed by Inoue et al. (8) and by Pizzo et al. (17, 18) and was reported by them to appear more strongly in the fibrin digests than in the fibrinogen digests, as we also find.

We shall call the COOH-terminal part of the \( \alpha \) chain, of molecular weight 44,000, the \( \alpha \) peptide for convenience. The question of whether this peptide is indeed observed intact in early fibrin digests, as our experiments suggest, must be settled by further experimentation.

Release of Fragments into the Clot Supernatant—Clot supernatant fragments are released more rapidly from fibrinogen than from fibrin (Figs. 6 and 7). The digestion of both fibrinogen and fibrin shows a rapid release of from 10 to 15% of the ultraviolet absorbing material as nonclottable material. After this, the release of fragments from fibrin levels off for some time. In contrast, with fibrinogen the initial rapid release is followed by an apparently steady digestion of all the clottable material to nonclottable fragments.

The breakdown of the \( \alpha \) chains of fibrin coincides with the release of the ultraviolet-absorbing material into the clot supernatant. SDS-polyacrylamide gel electrophoresis of the supernatant material has revealed the presence of a band with the mobility expected of the \( \alpha \) peptide. The increase in absorbance of the supernatant is between 10 and 15% of that obtained after complete digestion of fibrin, while the mass of the two \( \alpha \) peptides is 23% of that of the fibrinogen molecule. Mihalyi\(^2\) has recently shown that tryptic digestion of fibrinogen releases low molecular weight peptides derived from the COOH-terminal part of the \( \alpha \) chain, which constitute 23% of the total nitrogen but only 13% of the ultraviolet absorbance. We conclude that all available \( \alpha \) peptide has been released by the time the amount of ultraviolet-absorbing material released into the supernatant of fibrin gel temporarily levels off. The release of \( \alpha \) peptide correlates with the appearance of hyper-rigidity or the period in which no loss of rigidity is noticed, depending on the fibrinogen concentration, of fibrin gel and with the period in which the rigidity of the fibrin formed from predigested fibrinogen drops to a small fraction of the native value.

The results shown in Fig. 7b also indicate that the release of supernatant peptides of a 1:1 mixture of fibrin and fibrinogen proceeds at first as the digestion of fibrin alone. This indicates that plasmin has a considerably greater affinity for certain bonds in fibrin than for any bonds in fibrinogen.

Importance of the Order of Gelation and Lysis for the Rigidity of Fibrin—The results of the analysis by SDS-gel electrophoreses of the subunit structure of the early plasmin split product of fibrinogen and fibrinogen do not provide a basis for explaining the large difference in rigidity resulting from the split. For further study of this, fibrin monomers were prepared from intact fibrin gels and from fibrin gels that exhibited maximal hyper-rigidity following a small degree of plasmig digestion. These fibrin monomer solutions were then allowed to gel by a 10-fold dilution of the NaBr solution in the elastomer, and the development of clot elasticity was measured. The reclothed control gel, to which no plasmin had previously been added, showed greater than 90% of the rigidity of a fibrin gel obtained by clotting fibrinogen with thrombin in the same solvent. In contrast, the reclothed fibrin monomer that had been the constituent of a partly lysed gel showing hyper-rigidity exhibited only about 10% of the rigidity of the control clot. This indicates that the fiber conformation in the gel remains essentially intact when the COOH-terminal portions of the \( \alpha \) chains are removed but that this fiber conformation is not regained when the partially digested fibrin is dissolved and the solution is subsequently regelled.

DISCUSSION

The hydrolysis of fibrin by plasmin is generally regarded as the primary in vivo catabolic pathway for the destruction of fibrin gels. It has also been observed that activation of plasminogen is initiated at the same time as activation of the early phase of the clotting system and that plasmin generation and fibrin formation are linked by complex feedback control mech-
The data presented here delineate the interactions of plasmin and fibrin in the process of fibrin formation and in the early phase of the degradation of fibrin.

The most salient finding is that the first plasmic split appears to have no deleterious effect on the rigidity of the gel and presumably does not interfere directly with hemostasis.

The first event in the plasmin degradation of both fibrin and fibrinogen is the cleavage of a peptide (designated $\alpha_1$, molecu-
lar weight 44,000) from the COOH-terminal end of the α (or Aα) chain. There are no interchain disulfide bonds in this fragment, and it is released from the parent molecule. During plasmin digestion of fibrinogen, α1 is rapidly degraded to small peptides. This observation is in agreement with the description of fibrinogen degradation that has been developed by various groups over the past several years (1, 2, 4, 7). Our observations suggest that, during the degradation of fibrin, α1 is perhaps not degraded quite as rapidly but instead accumulates and that nearly all available α1 peptide is released before other bonds are cleaved.

Our results suggest that plasmin has a high affinity for the bond in the α chain that is to be split.3 The high affinity of plasmin for fibrin has also been described by Ambros and Markus (22), who proposed that this may serve to concentrate and retain active plasmin on the fibrin in the clot. It has also been proposed that, in vivo, plasmin has a higher affinity for fibrin than for fibrinogen (23). The present results demonstrate that in the presence of fibrin there is no free pool of plasmin available for the degradation of fibrinogen. Because fibrin is cleaved preferentially over fibrinogen, the affinity for the site of the first split in fibrin is higher than for cleavage sites in fibrinogen. Since no other peptides appear until the α chains have been cleaved, the affinity is higher than that for splits in other regions of fibrin.

The initial cleavage of the α chains of fibrin is a step with this important function: it delays both the weakening and the lysis of the clot for a considerable time (but not indefinitely), and it prevents plasmin from diffusing out of the clot during this time. Once the α chains have been cleaved, the cleavage of β and γ chains appears to proceed at a similar rate (24). The observed lowering of the rigidity begins some time after the α chains have been split, and the further release of peptides into the clot supernatant occurs somewhat later. This indicates that several splits, presumably of adjacent chains, are needed to cause a lowering of the rigidity and that even more are required before the core fragments, D and E (or dimers of fragment D held together by cross-linked γ chains), are released. Since the rigidity or modulus of elasticity is representative of the various mechanical properties of fibrin that are of physiological importance, it is apparent that the destructive effects of plasmin digestion are delayed by the high preference of plasmin for cleavage of one section of the α chain of fibrin.

3 A high affinity does not imply a high rate of cleavage. In fact, the initial cleavage of fibrin is slower than that of fibrinogen. It would be tempting to propose that the lower rate is due to shielding of plasmin-sensitive bonds from the enzyme by intermolecular contacts in the fibrin fiber. We find no support for this hypothesis in the results of our experiments.
also gives an increase of the rigidity. This premise is a natural one; a theory designed to relate the elasticity of fibrin to structure of fibers and network would have it as a postulate.

With this premise, the observed changes in the rigidity are interpreted as follows: (a) removal of the COOH-terminal portions of the α chains of fibrinogen causes a loss of certain polymerization sites; (b) in fibrin polymerized to a network of fibers, these same sites participate in intermolecular contacts, and when the COOH-terminal portions of the α chains are removed the contacts not only remain but increase slightly (in number or quality).

The second of the above conclusions excludes the possibility that the polymerization site is formed by the COOH-terminal portion of the α chain. This chain segment has an unusually hydrophilic amino acid composition (29). We suggest that it is one of the functions of this chain to maintain a polymerization site on the surface of the fibrin molecule. The enzymatic removal of the soluble chain section would allow the polymerization site to move to a less accessible position in the fibrin molecule. On the other hand, once the contacts have been formed as a part of the fiber structure, they stabilize the exposed conformation of the sites, obviating the solubilizing role of the COOH-terminal parts of the α chains. As judged from the increase of the rigidity that may accompany the removal of these soluble chains from inside the fibrin fiber, this removal appears to lead to an improvement of the intermolecular contacts. Since the split causes removal of predominantly hydrophilic chains totaling some 30% of the remaining mass, this is not an unreasonable consequence. It appears that only a short segment of the hydrophilic α1 peptide is crucial for exposure of the polymerization site, since fibrinogen Fraction I-8, which has α2 chains with molecular weights of 31,000 to 34,000 (30), forms fibrin with a rigidity indistinguishable from that of intact fibrin (Fraction I-4). This means that a hydrophilic segment with a molecular weight of only 6000 to 9000 is all that is essential for exposure of the polymerization site.

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