Determination of Functional Levels of Protein C, an Antithrombotic Protein, Using Thrombin-Thrombomodulin Complex

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Protein C is a vitamin K-dependent plasma protein. Activated protein C (protein C$_{ac}$) is a potent anticoagulant and enhances blood clot lysis. We have developed a functional assay for protein C in human plasma. The measurement of protein C is accomplished by the addition of thrombomodulin, an endothelial-cell-associated cofactor for protein C activation, and thrombin in a 1:1 molar complex. The activated protein C formed in the plasma is immunoadsorbed with goat anti-human protein C IgG-agarose. The immunoadsorbed activated protein C retains the ability to hydrolyze chromogenic substrates, and after unbound plasma proteins are removed by washing, the bound activated protein C is quantitated by incubation with the substrate H-D-phenylalanine-$p$-nitroanilide (S-2238). Normal individuals have functional protein C levels of 3.9-5.9 µg/ml, with a mean value of 4.8 µg/ml. Individuals undergoing warfarin anticoagulation and patients with advanced liver diseases have decreased levels, as do certain patients with evidence of intravascular clotting. Functional protein C levels correlate well with immunologic levels of the protein in the patient groups studied. Heparin enhances the rate of activated protein C inhibition, as monitored by recovery of activated protein C by immunoadsorption. A patient with recurrent venous thrombosis and abnormal functional protein C activity, but normal levels of antigen, has been identified.

**Protein C IS a vitamin K-dependent plasma protein. Activated protein C (protein C$_{ac}$) is a potent anticoagulant functioning at the levels of factors V and VIII in the clotting cascade.** Protein C, also promotes blood clot lysis, at least in part, by raising the levels of circulating plasminogen activator.

At present, no functional assay has been published for protein C in plasma. Studies of the role of protein C in hemostasis and thrombosis have been limited to the use of immunologic techniques. Using the Laurell rocket immunoelectrophoretic methods, patients with the combination of decreased protein C levels and recurrent thrombotic disease have been discovered, and decreased protein C levels have been measured in patients with intravascular coagulation.

Protein C can be activated relatively slowly by thrombin. However, an endothelial-cell-associated cofactor (thrombomodulin) has been described and isolated, that enhances the rate of protein C activation by thrombin. When bound to thrombomodulin, thrombin no longer clots fibrinogen.

The addition of a 1:1 molar complex of thrombin and thrombomodulin to human plasma results in the rapid, quantitative conversion of protein C to protein C$_{ac}$ and is the basis of the functional protein C assay described here.

**MATERIALS AND METHODS**

**Reagents**

Bovine thrombin was isolated following activation of the purified prothrombin with purified factor Xa, factor Va, phospholipid, and calcium. Bovine antithrombin-III was isolated as described. Rabbit lung thrombomodulin was isolated as described.

**Purification of Human Protein C**

Ten liters of fresh frozen human plasma was a generous gift from the Oklahoma Blood Institute. The plasma was thawed and 1 M benzamidine added to a final concentration of 5 mM. The plasma was chilled to 4°C in a melting ice bath, and 800 ml 1 M BaCl$_2$ was added dropwise over a 2-hr period while stirring the plasma at 4°C. The barium citrate was then centrifuged at 3,600 g at 4°C in a PR-6000 centrifuge (Damon/IEC, Needham Heights, MA) for 25 min. The precipitate was resuspended in 0.9% NaCl containing 0.2 M sodium citrate, 1 mM benzamidine, and 0.1 mg/ml soybean trypsin inhibitor (Sigma Chemical Co., St. Louis, MO) to a final volume of 2.6 liters. At 4°C, 288 ml 1 M BaCl$_2$ was again added dropwise and followed by centrifugation; the precipitate was resuspended in the same volume of saline-citrate, and the precipitation done a third time. The precipitate was then resuspended in 0.2 M ethylenediaminetetraacetic acid (pH 7.5) containing 5 mM benzamidine and 0.1 mg/ml soybean trypsin inhibitor to a final volume of 5 liters. At 4°C, finely ground ammonium sulfate was added to a 30% saturation. Following centrifugation, the precipitate was discarded. Ammonium sulfate was then added to 60% saturation. The precipitate was collected by centrifugation and resuspended in 150 ml 5 mM 2[N-morpholino]ethanesulfonic acid (MES) buffer, pH 6.0, containing 180 mM NaCl and 1 mM benzamidine. The sample was dialyzed 18 hr against two changes of the same buffer. The sample was then applied to a QAE Sephadex column (2.5 x 100 cm) (Sigma Chemical Co.), equilibrated with the dialysis buffer. The column was eluted with a linear NaCl gradient (from 180 mM to 500 mM) of 2,000 ml total volume.

Protein C in the eluate was assayed as previously described and fractions containing protein C pooled and dialyzed in 5 mM imidazole buffer, pH 6.0, containing 10 mM CaCl$_2$ and 1 mM benzamidine. After dialysis, the sample was applied to a 0.9 x 100 cm heparin-agarose column. The column was eluted with a linear NaCl gradient.

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gradient (0–500 mM) of 300 ml total volume in 5 mM imidazole buffer, pH 6.0, containing 10 mM CaCl₂ and 1 mM benzamidine. The protein C was eluted from the column and was stored at 4°C until used. Protein purity was judged by gel electrophoretic analysis (Fig. 1). Protein C fractions used were essentially free of contaminating protein. Minor contaminants in the protein C preparation may correspond to β-protein C as described by Kisiel. Protein C samples were dialyzed against 20 mM Tris buffer, pH 7.4, containing 150 mM NaCl immediately prior to use. Protein C was activated as previously described. Protein C concentration was calculated using the molar extinction coefficient of 16,000.

Preparation of Immunoadsorption Beads

A goat was injected with 1 mg human protein C in 1 ml Freund's complete adjuvant subcutaneously on 3 occasions 1 wk apart. At the fourth week, 1 mg human protein C was injected in Freund's incomplete adjuvant, one-half of the dose being given subcutaneously and one-half in the muscle of the rump. The animal was bled intravenously at weekly intervals thereafter for 5 wk. Goat IgG directed against human protein C was prepared. IgG was coupled to Bio-Gel agarose A-15 m, 50–100 mesh (Bio-Rad Laboratories, Richmond, VA) following cyanogen bromide activation. Approximately 5 mg IgG was bound per 1 ml agarose. The agarose was washed extensively with 4 M NaCl. To eliminate background amidolytic activity, immediately prior to use, the IgG-agarose was suspended in 20 mM Tris buffer, pH 7.4, and diisopropylfluorophosphate added to a final concentration of 1 mM, and the mixture was incubated for 30 min at 25°C. The IgG-agarose was then washed extensively with 150 mM NaCl in 20 mM Tris buffer, pH 7.4. For use in the assay, the beads were suspended in buffer at a ratio of 1 part beads to 2 parts buffer by vortexing immediately prior to addition to the assay reaction mixture. Immunoadsorption of normal plasma using equal volumes of IgG-agarose and plasma did not change the factor X or IX levels measured using one-step clotting assays, nor did such treatment alter the prothrombin time or partial thromboplastin time.

Immunoelectrophoretic Analysis

Protein C levels were measured immunologically using the Laurell rocket technique. Goat anti-human protein C IgG was used at 0.5% in 1% agarose gel plates. Human protein C supplemented barium-citrate-adsorbed human plasma was used to construct standard curves. The adsorbed plasma was prepared by adding 1 M BaCl₂ slowly to citrated plasma (80 ml BaCl₂/1 liter plasma) at 4°C. The precipitate was removed by centrifugation at 20,000 g for 10 min. The adsorbed plasma was dialyzed against 150 mM NaCl in 20 mM Tris buffer, pH 7.4, and frozen at −80°C prior to use.

Conditions of the Functional Protein C Assay

This functional assay is based on the activation of protein C in recalcified plasma by the thrombin-thrombomodulin complex. Direct quantitation of the activated protein C formed using a chromogenic substrate is not possible due to high background activity in the plasma. However, protein C bound to goat IgG anti-human protein C retains the ability to cleave small synthetic substrates. Therefore, the protein C was recovered from the plasma using IgG-agarose prior to quantitation (Fig. 2).

All determinations were made using plasma made from blood collected in sodium citrate (9 parts blood to 1 part 3.8% sodium citrate, pH 5.5). Samples were collected and processed in plastic; blood was chilled to 4°C in melting ice immediately upon collection,
and centrifuged at 4°C. Plasma was assayed immediately or stored at –80°C before assay.

The activation of protein C in plasma was carried out at 25°C in the following manner. To 25 μl of citrated plasma in a 1.5-ml disposable micro test tube (Bio-Rad Laboratories, Richmond, VA) was added 75 μl of 20 mM Tris buffer, pH 7.4, containing 150 mM NaCl, 8.3 mM CaCl₂, 0.12 μg bovine thrombin (0.29 U), and 0.24 μg thrombomodulin. A control sample of plasma to which only buffer and CaCl₂ were added was run simultaneously. The solution was mixed immediately and incubated at 25°C for 2 min. The level of thrombin–thrombomodulin used was selected to give rapid activation of the protein C in the dilute plasma (Fig. 3). The 2-min activation period was selected to give optimal protein C activation without formation of a fibrin clot in the recalcified plasma (Fig. 4).

Following the 2-min activation period, residual thrombin was inhibited by the addition of 50 μl of 800 μg/ml bovine antithrombin-III, with immediate mixing. One minute later, 100 μl of goat IgG anti-human protein C-agarose beads were added to the mixture. The sample was then mixed, using a vortex mixture, for 2 sec at 1-min intervals for 6 min. The IgG-agarose was then washed by adding 1.2 ml of 20 mM Tris buffer, pH 7.4, containing 150 mM NaCl. The contents of the tube were mixed for 1 min by repeated inversion of the tube and the precipitate by centrifugation in a Beckman Microfuge Model B (Beckman Instruments, Irvine, CA) for 10 sec. The supernatant was removed by aspiration, and the entire washing repeated 2 times.

After removal of the supernatant from the final wash, the protein C bound to the agarose beads was assayed with the chromogenic substrate S-2238 (Kabi Diagnostica, Sweden). The assay mixture contained 600 μl 0.2 mM S-2238 buffered with 20 mM Tris, pH 7.4, containing 150 mM NaCl and 0.1% Lubrol PX (Sigma Chemical Co.). The micro test tube was then mixed on a Unimixer (model 1305, Labline Biomedical Products, Inc., Melrose Park, IL) for 1 hr in a 37°C constant temperature room. At the end of the incubation period, the reaction was stopped with the addition of 100 μl M benzamidine HCl, followed by mixing. The immunoadsorption beads were removed by centrifugation in a microfuge, and the optical density of the supernatant was measured at 405 nm using a Beckman Model DU-5 spectrophotometer (Beckman Instruments, Irvine, CA). Specific chromogenic activity was 0.185 A_{405}/min/μg. Adsorption of the protein C on IgG agarose resulted in a 30% loss in specific chromogenic activity. The optical density of the sample blank (without thrombin–thrombomodulin in the reaction mix) was subtracted from that of the test tube and, in normal plasma, was approximately 25% of that seen in the sample tested with thrombin–thrombomodulin.

Barium-adsorbed human plasma supplemented with human protein C was used to construct standard curves (Fig. 5). A linear relationship between amounts of protein C added and the amount of synthetic substrate cleaved up to 10 μg protein C/ml plasma was observed.

Reproducibility of the Assay

Within-day and between-day variation of the assay was determined with 10 replicate determinations of a pooled normal plasma. The within-day value obtained was 5.3 ± 0.2 μg/ml (mean ± SD), and the between-day value was 5.3 ± 0.3 μg/ml.

Patient Populations

The study was approved by the University of Oklahoma Institutional Review Board, i.e., Human Experimentation Committee, and was in accordance with an assurance filed with and approved by the

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**Fig. 3.** Effect of thrombomodulin–thrombin concentration of protein C activation. Increasing concentrations of a 1:1 molar complex of thrombin–thrombomodulin complex were added to recalcified plasma (see Materials and Methods). The extent of protein C activation was measured as the amidolytic activity of the immunoadsorbed protein C, recovered after treatment of the plasma with thrombomodulin–thrombin.

**Fig. 4.** Effect of incubation time of thrombin–thrombomodulin complex in plasma on protein C activation. A 1:1 molar mixture of thrombin and thrombomodulin (final thrombomodulin concentration 3.2 μg/ml) was incubated with recalcified plasma for increasing lengths of time before immunoadsorption and quantitation of the protein C generated.

**Fig. 5.** Effect of protein C concentration on amidolytic activity observed. Barium-adsorbed human plasma was supplemented with purified human protein C, and the amidolytic activity was measured after activation of the protein C in the barium-adsorbed plasma with thrombin–thrombomodulin (final thrombomodulin concentration, 3.2 μg/ml).
Department of Health, Education, and Welfare. All patients gave informed consent. Patients receiving warfarin anticoagulation had been stabilized on a dose of warfarin at least 1 wk prior to testing. Normal volunteers ranged from 22 yr to 61 yr of age; the mean age was 35 yr. Patients with cirrhosis of the liver had a biopsy-proven diagnosis. Patients with intravascular clotting had platelet counts below 80,000, prothrombin times and partial thromboplastin times 5 sec or more above the normal ranges and fibrinogen levels of 120 mg/dl or less. Patients with disseminated intravascular coagulation (DIC) all had fibrin split products over 40 μg/ml.

**Description of Patient**

The functionally deficient patient was a 25-yr-old man with a history of severe recurrent venous thrombosis. At age 14, the patient had venographically documented deep femoral vein thrombosis with pulmonary emboli, documented by lung scan. The patient experienced right calf thrombosis at age 19 yr. There was no family history of thrombosis. Plasma samples were drawn from the patient while he was not receiving warfarin or heparin. The prothrombin time, partial thromboplastin time, thrombin time, factor V and VIII levels, antithrombin-III level, and fibrin split products were all within normal limits.

**RESULTS**

Functional protein C levels were determined in 20 normal individuals (Fig. 6). The mean value was 4.8 ± 1.0 μg/ml (mean ±2 SD). This is in agreement with the levels of protein C detected immunologically by Griffin et al. and Stenflo et al. The functional protein C levels in the 20 normal individuals agreed well with those determined in the same individuals by Laurell rocket immunoelectrophoresis (correlation coefficient r = 0.89, p < 0.01) (Figs. 7 and 8). Patients with cirrhosis of the liver had functional protein C levels ranging from 1.2 to 4.4 μg/ml, with a mean value of 2.5 μg/ml. Patients receiving warfarin anticoagulation had functional protein C levels between 2.0 μg/ml and 2.5 μg/ml, with a mean value of 2.6 μg/ml. In the cirrhotic patients and those on warfarin anticoagulation, there was a correlation between the functional protein levels and those measured by rocket electrophoresis (r = 0.80, p < 0.05). Four patients with intravascular coagulation were found to have functional protein C levels of less than 3.0 μg/ml. This is in agreement with the findings of Griffin et al., who observed decreased levels of immunologically detectable protein C in hospitalized patients with intravascular coagulation.

A patient with severe recurrent deep venous thrombosis with decreased functional protein C levels was identified using this functional protein C assay. The patient was examined at a time when he was not receiving heparin or warfarin. His clotting parameters were normal (see Materials and Methods). The patient's functional level of protein C was 1.7 μg/ml on one occasion and 1.9 μg/ml on a second occasion. The immunologic level was 4.8 μg/ml on both occasions. The ratios of functional activity to immunologically detected protein were 0.35 and 0.40. These ratios are both less than the normal functional activity/immunologic level ratios, ranging from 1.10 to 0.90, found in 20 normal individuals.

Since a number of patients with thrombosis receive heparin anticoagulation, the effect of heparin on the assay was examined (Fig. 9). At heparin levels above...
In normal pooled human plasma, supplemented with sodium heparin at the levels indicated, the protein C activity was measured. Heparin concentration is shown in U/ml.

Influence of heparin on inhibition of activated protein C in plasma. Plasma samples from 3 normal individuals were assayed for disappearance of activated protein C activity, as described in Fig. 8. Samples without heparin (○) and with 2 U heparin/ml (■) were assayed for each individual. The addition of 2 U heparin/ml plasma resulted in a 2-3-fold increase in the rate of activated protein C inhibition over the first 20 minutes of the reaction. Increasing concentrations of heparin were tested in a similar manner (Fig. 12), and maximal enhancement of activated protein C inhibition was observed at concentrations of 7.5 U/ml and above.

DISCUSSION

The functional protein C assay we describe provides a rapid, reproducible method of measuring protein C in normal and patient plasma. The assay takes advantage of the alteration of thrombin substrate specificity brought about by the binding of thrombin to thrombomodulin. Thrombin bound to thrombomodulin clots...
were incubated for 20 mm at 37°C. Residual activated protein C inactivation. Replicate samples of normal plasma containing COMP. NIXON, AND ESMON

The addition of thrombin alone at the concentration used in the protein C assay (1.6 μg/ml) directly to plasma results in clot formation in less than 10 sec. However, the addition of a complex of 1.6 μg/ml thrombin and 3.2 μg/ml thrombomodulin does not result in clot formation for longer than 8 min. This permits the activation of protein C in plasma without requiring either removal of fibrinogen or adsorption of protein C and the other vitamin K-dependent plasma proteins prior to activation of the protein C.

The assay tests two functional aspects of protein C: (1) the ability to function as a substrate for the thrombin–thrombomodulin complex and (2) following activation, the capacity to hydrolyze synthetic substrates. Based on this functional assay alone, patients with normal apparent levels of functional protein C cannot be unambiguously diagnosed as having a fully functional protein C molecule. In addition to the functions tested in this assay, activated protein C functions as both an anticoagulant and profibrinolytic agent. Current information suggests that the anticoagulant activity requires interaction with phospholipid, protein S, Ca\(^2+\), and the target molecules factors V(a) and VIII(a). This assay does not test any of these interactions directly. Since the mechanisms of protein C stimulation of fibrinolysis are unknown, assays for this function must await further basic studies. Despite these limitations, the rapidity and reproducibility of the assay represent an improvement over immunologic methods.

Furthermore, as evidenced by the patient with functional protein C deficiency, the assay can detect some functional deficiencies not detected by immunologic methods.

The observed correlation between functional and immunologic levels of protein C in the plasma of patients receiving warfarin suggests that, under the conditions of the functional assay, all the protein C molecules in the plasma are being activated. If protein C molecules are present in these plasmas, which are incompletely carboxylated or totally lacking γ-carboxyglutamic acid residues, these forms are being activated. The activation of these warfarin forms of protein is compatible with the findings of Esmon et al.\(^21\) that modified protein C, which has had the γ-carboxyglutamic acid region removed by chymotrypsin cleavage, is converted to the activated form by the soluble thrombin–thrombomodulin complex with activation parameters identical to native protein C. Development of an assay to distinguish between native and modified forms of protein C will require modification of the method we have outlined.

The measurement of activated protein C inhibition by the immunoadsorption method has several advantages over the assay of the activated protein in dilute plasma previously described. First, at the time the residual protein C is measured, other plasma proteins and inhibitors have been removed by washing. For example, there is no need to add antikallikrein antibodies to the assay to reduce background activity. Secondly, heparin is not required in the assay. This is of importance since we, in agreement with Canfield and Kisiel,\(^22\) find that heparin significantly increases the rate of activated protein C inhibition in plasma. This effect of heparin on activated protein C inhibition may have implications concerning the use of heparin in disease states where protein C activation may be occurring, such as disseminated intravascular coagulation. These data indicate that heparin, like warfarin, may inhibit both procoagulant and anticoagulant pathways.

Immunoadsorption of activated protein C from plasma may provide a useful alternative method for the study of activated protein C inhibition by its plasma proteinase inhibitor(s). Available methods for the assay of activated protein C inhibition in plasma are complex and have led to two different conclusions about the role of the activated protein C inhibitor in human disease. Recently, Marlar and Griffin\(^30\) suggested that a deficiency of the activated protein C inhibitor may be responsible for factor V/VIII deficiency, and these observations were confirmed by Giddings et al.\(^21\) Using somewhat different assay conditions, Canfield and Kisiel\(^32\) observed normal levels of activated protein C inhibitory activity in the factor-V/VIII-deficient plasmas they studied. The use of the immunoadsorption assay described here may prove helpful in resolving this apparent discrepancy.

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FUNCTIONAL LEVELS OF PROTEIN C

REFERENCES


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