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(54) **FIBRIN SEALANT**

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(57) **ABSTRACT**

A fibrin sealant, comprises (a) thrombin, (b) fibrinogen, (c) polyP, and (d) calcium. The thrombin and the fibrinogen are separated prior to application.

20 Claims, 6 Drawing Sheets

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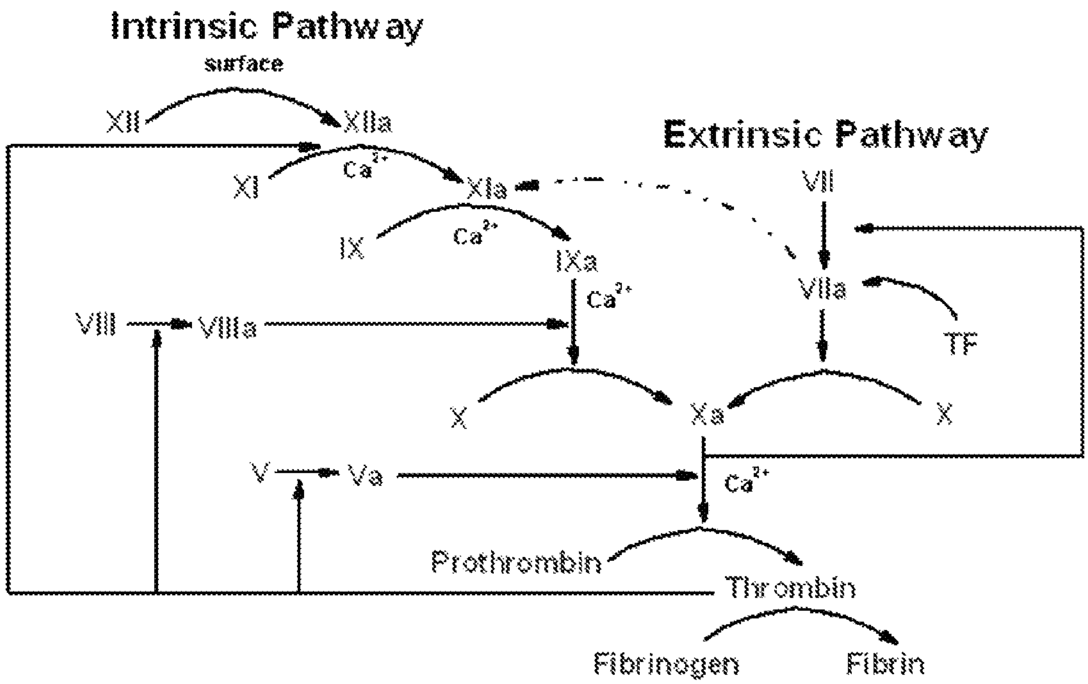

Intrinsic Pathway
surface
XII
XIIa
XI
Ca^{2+}
XIa
Extrinsic Pathway
VII
IX
Ca^{2+}
IXa
VIIa
Ca^{2+}
VIII
VIIIa
TF
X
Xa
X
V
Va
Ca^{2+}
Prothrombin
Thrombin
Fibrinogen
Fibrin

FIG. 1(A)

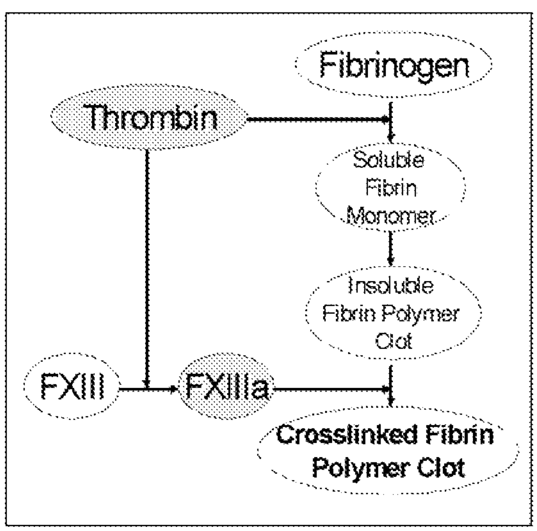

Fibrinogen
Thrombin
Soluble Fibrin Monomer
Insoluble Fibrin Polymer Clot
FXIII
FXIIIa
Crosslinked Fibrin Polymer Clot

FIG. 1(B)

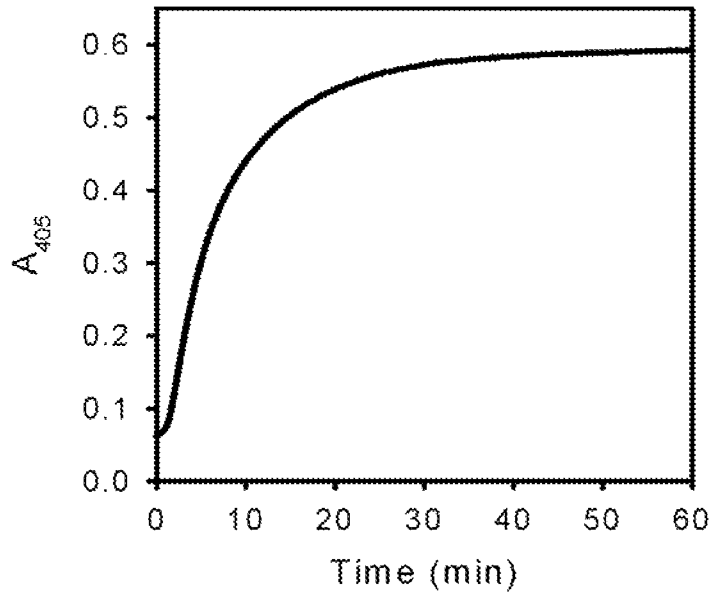

0.6
0.5
0.4
0.3
0.2
0.1
0.0
A_{405}
0
10
20
30
40
50
60
Time (min)

FIG. 2

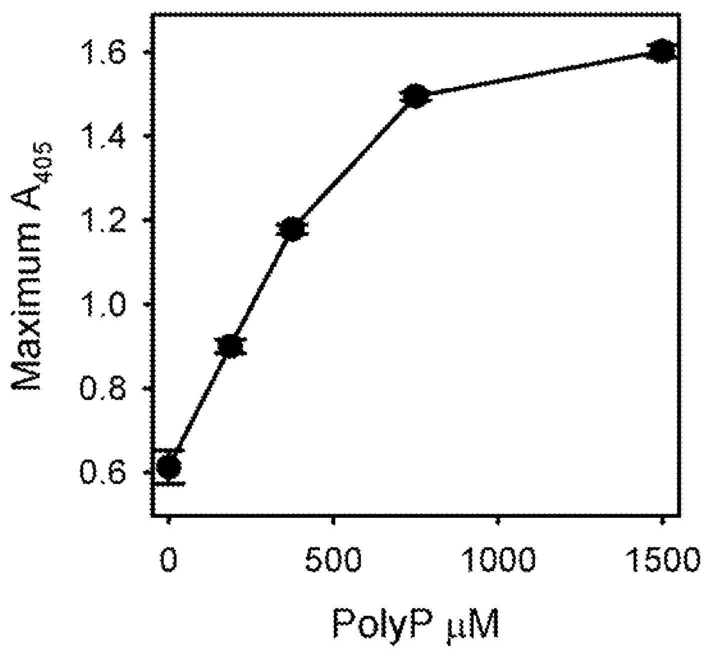

1.6
1.4
1.2
1.0
0.8
0.6
Maximum A_{405}
0
500
1000
1500
PolyP μM

FIG. 3

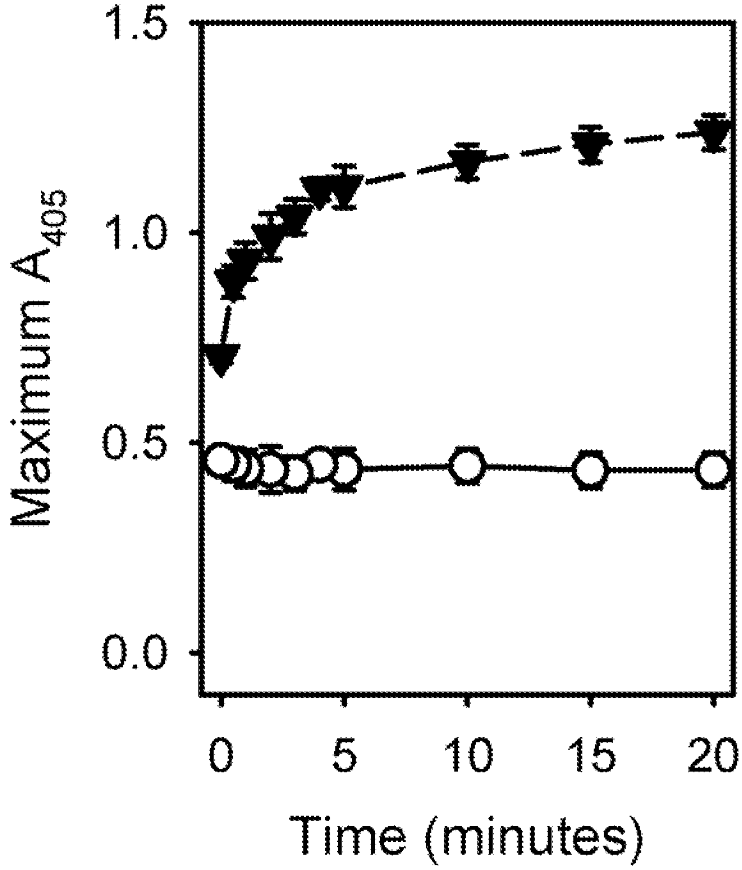


FIG. 4

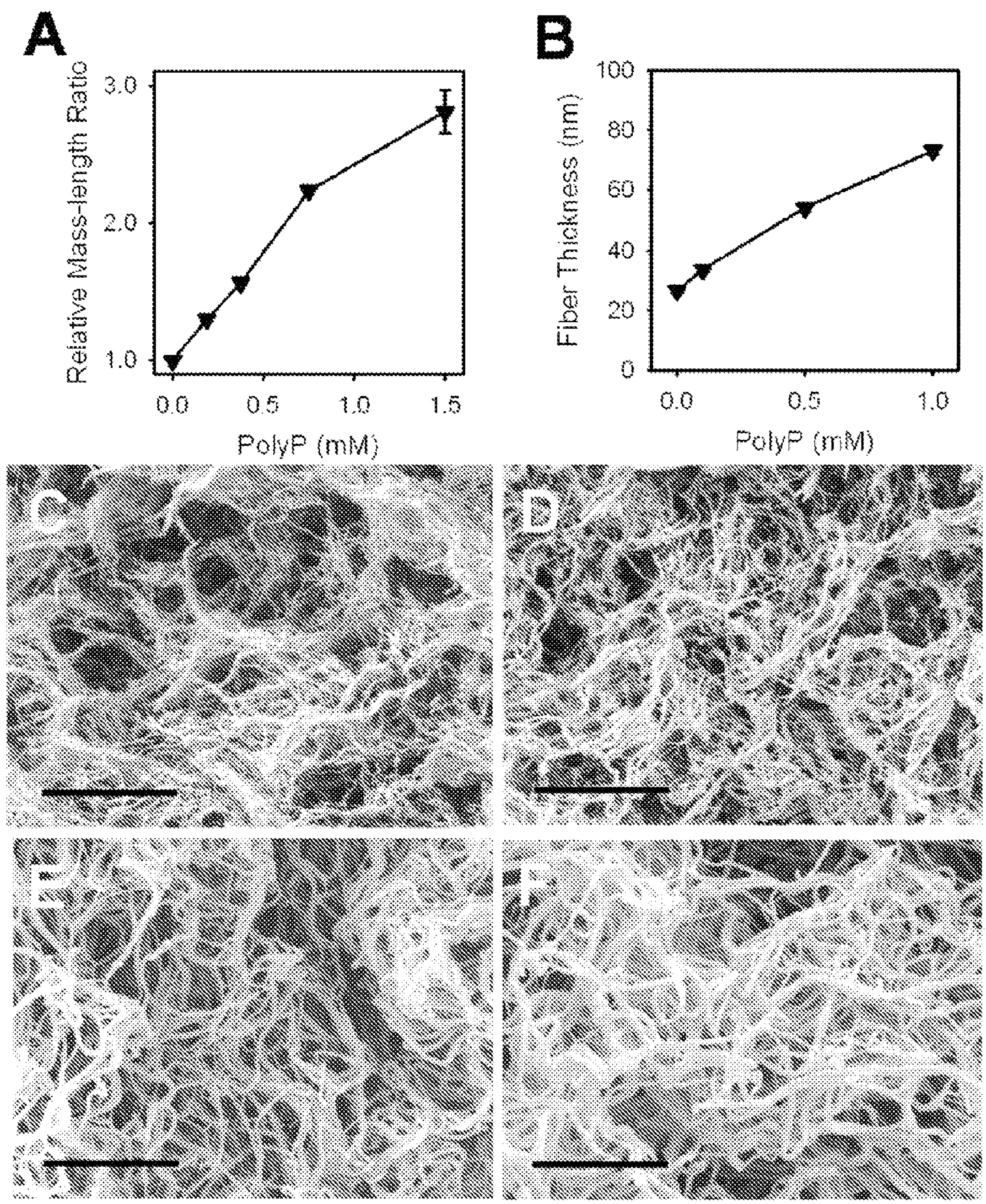

A
Relative Mass-length Ratio
3.0
2.0
1.0
0.0
0.5
1.0
1.5
PolyP (mM)
B
Fiber Thickness (nm)
100
80
60
40
20
0
0.0
0.5
1.0
PolyP (mM)
C
D
E
F

FIG. 5

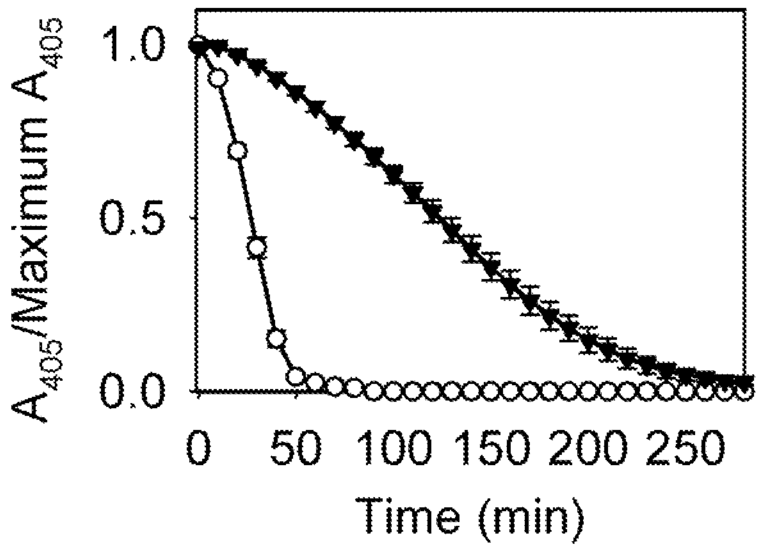


FIG. 6

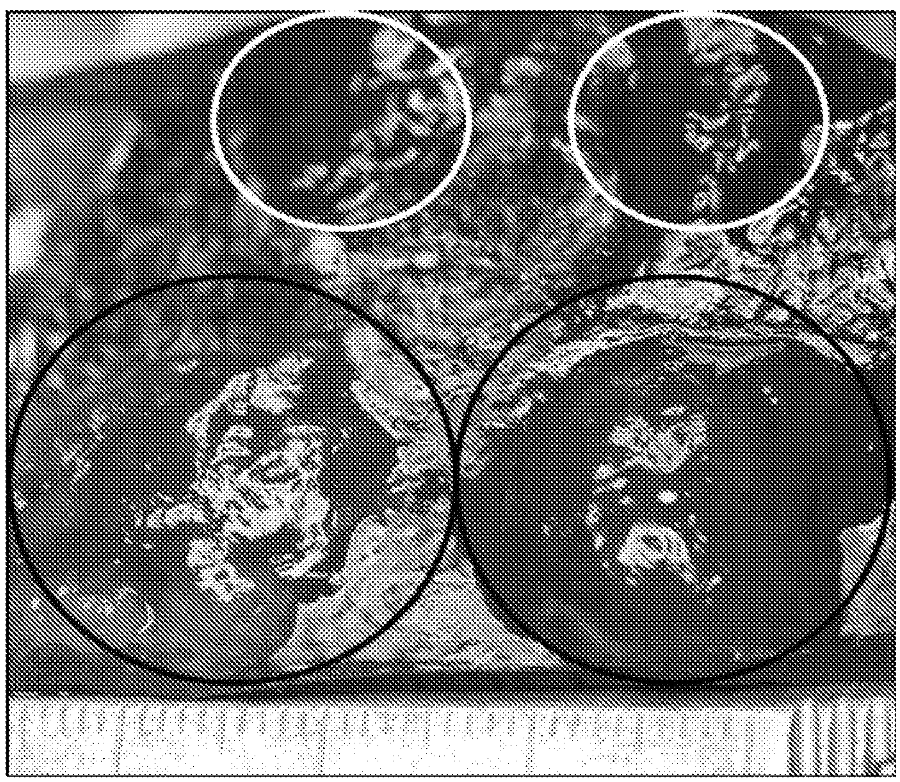


FIG. 7

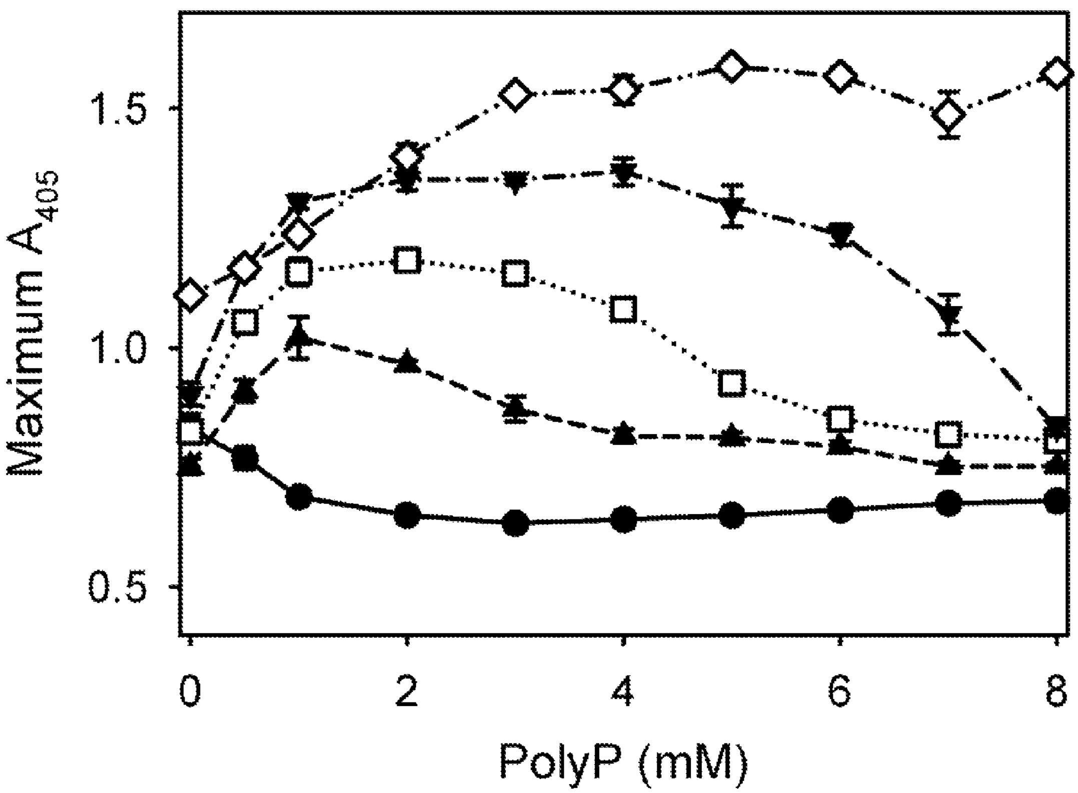


FIG. 8

FIBRIN SEALANT

CROSS REFERENCE TO RELATED APPLICATION

This application claims priority to provisional application No. 60/978,009 entitled "Fibrin Sealant" filed 5 Oct. 2007, the entire contents of which are hereby incorporated by reference, except where inconsistent with the present application.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This application was funded in part under the following research grants and contracts: NIH(NHLBI) Grant No. R01 HL47014. The U.S. Government may have rights in this invention.

BACKGROUND

A schematic of the clotting cascades is shown in FIG. **1**(A). In the figure the various clotting factors are indicated by their Roman numeral (i.e., factor VII is indicated by VII). The intrinsic pathway (also referred to as the contact pathway of blood coagulation) is initiated when contact is made between blood and certain artificial surfaces. The extrinsic pathway (also referred to as the tissue factor pathway of blood coagulation) is initiated upon vascular injury which leads to exposure of tissue factor (TF) (also identified as factor III). The dotted arrow represents a point of cross-over between the extrinsic and intrinsic pathways. The two pathways converge at the activation of factor X to Xa. Factor Xa has a role in the further activation of factor VII to VIIa. Active factor Xa hydrolyzes and activates prothrombin to thrombin. Thrombin can then activate factors XI, VIII and V furthering the cascade. Ultimately, the role of thrombin is to convert fibrinogen to fibrin, which forms clots.

Fibrinogen is the most abundant coagulation protein in blood. The formation of a fibrin clot from fibrinogen is the terminal step in the coagulation cascade. Soluble fibrin monomers, which are created when thrombin cleaves fibrinogen, spontaneously polymerize to form a three dimensional network of insoluble fibrin fibrils. Clotting of fibrinogen by thrombin is one of the few steps in the clotting cascade that does not require calcium ions. The resulting fibrin clot structure can be further stabilized via covalent cross-linking of the fibrils through the action of the transglutaminase enzyme, factor XIIIa (FIG. **1** (B)) [26].

Fibrin sealant, also referred to as "fibrin glue" or "fibrin tissue adhesive," is a surgical hemostatic agent derived from plasma coagulation proteins. Fibrin sealants are widely used to control bleeding in a variety of surgical settings, and their use has increased due to the advent of minimally invasive surgical procedures which necessitate meticulous hemostasis for adequate visualization of the surgical field [27]. Fibrin sealants can be used for hemostasis, wound closure, and tissue sealing and have been advocated as the agents that are closest to approaching the ideal operative sealant. In contrast to synthetic adhesives, fibrin sealants have the advantage of being biocompatible and biodegradable, and they are not associated with inflammation, foreign body reactions, tissue necrosis, or extensive fibrosis. Reabsorption of the fibrin clot is achieved during normal wound healing within days to weeks of application, depending on the type of surgery, the proteolytic activity of the treated site, and the amount of sealant used.

Fibrin sealants are typically derived from plasma proteins and contain two primary components: fibrinogen and thrombin. These two components are stored separately and are mixed during application, whereupon the applied mixture forms a fibrin clot on the wound surface to prevent further hemorrhage. The sealant may be applied with a needle, as a spray, or using other devices. When fibrinogen and thrombin are mixed (during application of fibrin sealant to a wound), the fibrinogen component is converted to fibrin monomers. Polymerization of fibrin monomers results in the formation of a semi-rigid fibrin clot that is capable of interacting covalently and non-covalently with tissue structures. The clot may be further stabilized by cross-linking of the fibrin alpha and gamma chains in a reaction catalyzed by activated factor XIII. This cross-linking stimulates adherence of fibroblasts and promotes their normal growth into the clot. By mimicking the latter stages of the physiologic coagulation system, these processes allow fibrin sealants to arrest blood loss and assist the wound healing process.

Most commercially available fibrin sealants contain purified, virally inactivated human fibrinogen and either human or bovine thrombin, optionally with different quantities of factor XIII and anti-fibrinolytic agents (such as bovine aprotinin). Some of the currently available fibrin sealants are summarized in Table 1. Both Tisseel and Beriplast P are marketed as a two-component kit: component one contains lyophilized pooled human fibrinogen/factor XIII concentrate, which is reconstituted with antifibrinolytic solution (aprotinin); and component two is bovine thrombin reconstituted with 40 mM $CaCl_2$. Tisseel is supplied as a lyophilizate or frozen, whereas Beriplast P is supplied as a lyophilizate. The two-component fibrin sealant is usually applied through a double barreled syringe system, which allows simultaneous application of equal volumes of the fibrinogen and thrombin through a blunt-ended needle or spray tip. Virus inactivation of fibrinogen and thrombin is carried out by a variety of methods, including two-step vapor heat at 60° C. and 80° C., pasteurization (liquid solution, 10 hours at 60° C.), or solvent-detergent treatment, with pasteurization, nanofiltration, or exposure to ultraviolet light.

TABLE 1

Composition of fibrin sealants

Sealant	Form	Human fibrinogen (mg/mL)	Human factor XIII (U/mL)	Human or bovine thrombin (IU/mL)	Bovine aprotinin (KIU/mL)
Tisseel ®, Tissucol ® (Duo Baxter-Immuno AG, Austria)	Frozen solution	70-110	10-50	500	3,000

TABLE 1-continued

Composition of fibrin sealants

Sealant	Form	Human fibrinogen (mg/mL)	Human factor XIII (U/mL)	Human or bovine thrombin (IU/mL)	Bovine aprotinin (KIU/mL)
Tisseel ®, Tissucol ® (Kit Baxter-Immuno AG, Austria)	Lyophilizate	70-110	10-50	500	3,000
Tisseel ® (VH Kit Baxter-Immuno AG, USA)	Lyophilizate	75-115		500	3,000
Beriplast P ® (Aventis Behring, Germany)	Lyophilizate	90 (65-115)	60 (40-80)	500 (400-600)	1,000
Hemaseel ® (APR Haemacure, Canada) (As Tisseel VH Kit Baxter-Immuno)	Lyophilizate	75-115		500	3,000
Quixil ® (Omrix Biopharmaceuticals SA, Israel)	Frozen solution	60-100	None	1,000	None (tranexamic acid 92 mg/mL)
Bolheal ® (Kaketsuken Pharmaceutical, Japan)	Lyophilizate	80	75	250	1,000
Biocol ® (LFB-Lille, France)	Lyophilizate	127	11	558	3,000
VIGuard F.S. ® (Vitex: VI Technologies, USA)	Lyophilizate	50-95	3-5	200	None

Previous studies showed that polyP shortens the clotting time of human plasma by acting at two steps in the clotting cascade: (a) activating the contact pathway of blood clotting, and (b) accelerating the conversion of factor V to Va [20]. Since polyP did not shorten clotting times when thrombin was added to plasma, it was previously concluded that polyP exerts its procoagulant effects at points in the clotting cascade upstream from thrombin.

SUMMARY

In a first aspect, the present invention is a fibrin sealant, comprising (a) thrombin, (b) fibrinogen, (c) polyP, and (d) calcium. The thrombin and the fibrinogen are separated.

In a second aspect, the present invention is a fibrin sealant kit, comprising (I) a first composition comprising (a) thrombin, (II) a second composition comprising (b) fibrinogen, (c) polyP, and (d) calcium, and (III) a fibrin sealant applicator.

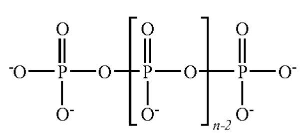
In a third aspect, the present invention is a method of controlling bleeding, comprising applying the fibrin sealant to a source of blood loss of a patient. The fibrin sealant comprises (a) thrombin, (b) fibrinogen, (c) polyP, and (d) calcium. The thrombin and the fibrinogen are separated until application.

DEFINITIONS

XIII, FXIII or factor XIII means coagulation factor XIII.

XIIIa, FXIIIa or factor XIIIa means coagulation factor XIIIa.

PolyP$_n$ means a compound of the following formula:



where the value of n is equal to the number of PO_3 units in the molecule, and n is at least 3. Polyphosphate (polyP) is a generic term for polyP$_n$, including mixtures, where n of each polyP$_n$ is at least 3. Concentrations of polyphosphate and any polyP$_n$ may be expressed as “phosphate equivalents”, which means the concentration of PO_3 moieties (for example, 1 μM polyP$_{75}$ is the same as 75 μM phosphate equivalents of polyP$_{75}$). All amounts and concentrations of polyP and polyP$_n$ are expressed herein as phosphate equivalents. Also included are salts, esters, anhydrides of polyphosphate, as well as cyclic polyphosphates.

Thrombin means any protein that exhibits thrombin activity of human thrombin. Thrombin activity of a protein is determined by comparing the concentration of the protein necessary to form the same amount of fibrin clots as 1 nM human thrombin, using the following assay: fibrin clots are formed in 96-well polystyrene microplates using 2.6 mg/mL human fibrinogen in TBS plus thrombin (or the protein being tested for thrombin activity) in TBS added to trigger clot formation in a total volume of 200 μL. Clotting is evaluated by monitoring the change in turbidity (A_{405}) for 1 hour at room temperature using a microplate reader. Thrombin may be isolated from blood, or may be made recombinantly. Examples of thrombin include human thrombin, rabbit thrombin and bovine thrombin.

Fibrinogen means any protein that exhibits fibrinogen activity of human fibrinogen. Fibrinogen activity of a protein is determined by comparing the concentration of the protein necessary to form the same amount of fibrin clots as 2.6 mg/mL human fibrinogen, using the following assay: fibrin clots are formed in 96-well polystyrene microplates using fibrinogen (or the protein being tested for fibrinogen activity) in TBS plus 1 nM human thrombin in TBS added to trigger clot formation in a total volume of 200 μL. Clotting is evaluated by monitoring the change in turbidity (A_{405}) for 1 hour at room temperature using a microplate reader. Fibrinogen may be isolated from blood, or may be made recombinantly.

Examples of fibrinogen include human fibrinogen, rabbit fibrinogen and bovine fibrinogen.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**(A) is a schematic of the clotting cascades.

FIG. **1**(B) is a schematic of the terminal steps in the blood clotting cascade.

FIG. **2** is a typical graph of the time-dependent change in optical density (measured at 405 nm) observed as a mixture of 2.6 mg/mL fibrinogen and 1 nM thrombin forms a fibrin clot. The final clot turbidity (maximum A_{405}) is typically its optical density at 60 minutes.

FIG. **3** is a graph showing the enhancement of the final turbidity of fibrin clots formed by mixing 2.6 mg/mL fibrinogen and 8 nM thrombin with various concentrations of polyP. The solution also contained 2.5 mM calcium chloride.

FIG. **4** is a graph of the time dependence of preincubation of fibrinogen with polyP and Ca^{2+} versus final clot turbidity. Reactions contained 2.6 mg/mL fibrinogen preincubated for the indicated times in the presence of 2.5 mM $CaCl_2$ with 1 mM polyP (▼) or without polyP (O), after which clotting was initiated with 8 nM thrombin.

FIG. **5**(A) is a graph of the relative mass-length ratios of fibrin clots formed by clotting 2.6 mg/mL fibrinogen with 3 nM thrombin in the presence of 2.5 mM calcium ions and varying concentrations of polyP. The calculated mass-length ratios were normalized to the value obtained in the absence of polyP.

FIG. **5**(B) is a graph of fibril thickness measured on scanning electron micrographs of fibrin clots that were formed by clotting 2.6 mg/mL fibrinogen with 3 nM thrombin in the presence of 2.5 mM calcium ions and varying polyP concentrations.

FIGS. **5**(C), **5**(D), **5**(E) and **5**(F) are scanning electron micrographs of fibrin clots formed in the presence and absence of polyP. Clots were formed by preincubating 2.6 mg/mL fibrinogen for 15 minutes in the presence of 2.5 mM $CaCl_2$ with (C) No polyP; (D) 100 μM polyP; (E) 500 μM polyP, or (F) 1 mM polyP, after which clotting was initiated in each case with 3 nM thrombin. Bar=2 μm.

FIG. **6** is a graph of the time course of fibrinolysis of fibrin clots. Fibrinogen (1 mg/mL) was preincubated for 15 minutes in the presence of 2.5 mM $CaCl_2$ with 1 mM polyP (▼) or without polyP (O), after which 8 nM plasmin was added followed immediately by 1 nM thrombin. Fibrin clots were allowed to form for 30 minutes, after which their turbidities were measured. The data are plotted as A_{405} values normalized to the initial A_{405} value for each curve.

FIG. **7** is a photograph of clots formed after application of a fibrin sealant to spleen surface wounds in a porcine model of surgical bleeding. The lower two wounds (dark circles) were treated with a fibrin sealant prepared with fibrinogen (33.6 mg/mL) that had been preincubated with 1 mM polyP in the presence of 2.5 mM $CaCl_2$, then mixed with an equal volume of thrombin (100 IU/mL). The upper two wounds (white circles) were treated with a fibrin sealant prepared with the same fibrinogen and thrombin concentrations but without polyP.

FIG. **8** is a graph of the concentrations of both polyP and Ca^{2+} versus final clot turbidity. Reactions contained 2.6 mg/mL citrate-free fibrinogen, which was preincubated for 15 minutes with $CaCl_2$ and the indicated concentrations of polyP (x axis), after which clotting was initiated with 1 nM thrombin. The Ca^{2+} concentrations were 0 (●), 2 mM (▲), 2.5 mM (□), 3 mM (▼), and 5 mM (◇).

DETAILED DESCRIPTION

The present invention is based on the discovery that, while polyP does not alter the clotting time induced by thrombin, it does enhance the structure of the resulting fibrin clots. In the present study, fibrin clots were formed by mixing fibrinogen and thrombin. This is a much simpler clotting system than whole plasma, and it also forms the basis for commercially available fibrin sealants, which are widely used as topical hemostatic agents to control bleeding during surgery. PolyP enhanced the structure of fibrin clots by causing the formation of thicker fibrils. Fibrin clots formed in the presence of polyP were also considerably more resistant to fibrinolysis by plasmin. And finally, in experiments using a pig model of surgical bleeding, it has been found that a topical fibrin sealant containing thrombin and fibrinogen was considerably more effective in controlling bleeding when polyP was added to the fibrinogen. Interestingly, polyP was only able enhance fibrin clot structure in the presence of calcium ions. Calcium ions are not required for thrombin to cause the clotting of fibrinogen, although it does have a small effect on the clot structure.

The fibrin sealants of the present invention contain thrombin, fibrinogen, polyP and calcium ions (Ca^{2+}). Prior to use, the sealant is provided as two separate components, preferably in the form of a kit, one component containing the thrombin, and the other component containing the fibrinogen. Preferably, the polyP is present in the component containing the fibrinogen, and preferably the calcium ions are also provided in the component containing the fibrinogen. Alternatively, the polyP and the calcium ion may be provided as a third component; or as third and fourth components. Less preferably, the polyP, the calcium ions, or both, may be provided in the component containing thrombin, or both the component contain thrombin and the component containing fibrinogen.

The polyP contains at least 3 PO_3 moieties. Preferably, polyP$_n$ with n of at least 25 may be used, for example n=25-1000, more preferably, n=25-100 (including 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43 and 44), more preferably n is at least 45, including 45-1000 (including 70, 71, 72, 73, 74, 75, 76, 77, 78, 79 and 80). The amount of polyP or polyP$_n$ per mg of fibrinogen is preferably at least 0.03 micromoles, such as 0.03 to 10 micromole, more preferably 0.04 to 4 micromoles, including 0.05, 0.1, 0.25, 0.5, 1, 2 and 3 micromoles.

Preferably, the calcium ions are provided as calcium chloride. The amount of calcium ions per mg of fibrinogen is preferably at least 0.1 micromoles, such as 0.1 to 100 micromoles, more preferably 0.3 to 10 micromoles, including 0.4, 0.5, 0.75, 1, 2, 5, and 8 micromoles.

Preferably the fibrinogen is mammalian fibrinogen, more preferably rabbit, bovine or human fibrinogen, most preferably human fibrinogen. Preferably, the fibrinogen has been subject to virus inactivation. Preferably, the amount of fibrinogen is at least 1 mg/mL, such as 1 to 500 mg/mL, more preferably 2.5 to 200 mg/mL, most preferably 25 to 125 mg/mL.

Preferably the thrombin is mammalian thrombin, more preferably rabbit, bovine or human thrombin, most preferably human thrombin. Preferably, the thrombin has been subject to virus inactivation, or produced by recombinant means, or both. Preferably, the amount of thrombin per mg of fibrinogen is at least 10 pmoles, such as 10 pmoles to 10 nmoles, more preferably 25 pmoles to 4 nmoles, including 50 pmoles, 100 pmoles, 250 pmoles, 500 pmoles, 1 nmoles, 2 nmoles, and 3 nmoles. Alternatively, the amount of thrombin per mg of fibrinogen is preferably at least 1 IU, such as 1 to 100 IUs, more preferably 4 to 50 IUs, including 5, 10, 20, 25, 30, 35, 40 and 45 IUs.

Optionally, the fibrin sealant may contain a cross-linking agent, such as factor XIII. When factor XIII is used as a cross-linking agent, it is present in an amount, per mg of fibrinogen, of at least 0.01 U, such as 0.01 to 5 U, more preferably 0.05 to 2 U, including 0.1, 0.2, 0.3, 0.4, 0.5, 0.75, 1 and 1.5 U. The cross-linking agent may be present in the component containing thrombin, the component containing fibrinogen, in a separate component, or two or more of these components. Preferably, if factor XIII is present, the factor XIII is mammalian factor XIII, more preferably rabbit, bovine or human factor XIII, most preferably human factor XIII. Preferably, the factor XIII has been subject to virus inactivation, or produced by recombinant means, or both.

Optionally, the fibrin sealant may contain a fibrinolysis inhibitor. Examples include aprotinin and tranexamic acid. Preferably, the fibrin sealant contains aprotinin, in an amount, per mg of fibrinogen, of at least 1 KIU, such as 1 to 500 KIU, more preferably 10 to 100 KIU, including 20, 30, 40, 50, 60, 70, 80 and 90 KIU. The fibrinolysis inhibitor may be present in the component containing thrombin, the component containing fibrinogen, in a separate component, or two or more of these components. Preferably, the fibrinolysis inhibitor has been subject to virus inactivation.

Immediately prior to use, each component of the fibrin sealant should be a liquid. Prior to use, the fibrin sealant may be in a variety of forms, including a frozen solution or as a lyophilizate. The liquid may also contain a pharmaceutically acceptable carrier, such as saline, a buffer solution, or water. Preferably, the fibrin sealant is sterile. A variety of applicators may be used to apply the two-, three-, or more part composition, such as a double-barreled syringe, or a spray applicator. The fibrin sealant can also be applied as drops for separate containers, and mixed at the application site.

EXAMPLES

In Vitro Results (Fibrin Clot Structure)

The in vitro studies reported here utilize a microplate-based method to evaluate the formation of fibrin clots, which are prepared by mixing together purified fibrinogen and thrombin. Once fibrinogen is cleaved to fibrin, the fibrin monomers spontaneously polymerize to yield a three-dimensional gel, or clot. These fibrin polymers scatter visible light, resulting in increased turbidity which can monitored spectrophotometrically to detect clotting. FIG. **2** shows an example of clot formation detected by monitoring the change in optical density.

It has now been found that polyP increases the final turbidity of clots formed by the action of thrombin on fibrinogen (FIG. **3**). Optimal enhancement of final clot turbidity was observed at approximately 1 mM polyP (expressed as concentration of phosphate monomer), but the optimal polyP concentration also depended on the calcium concentration (FIG. **8**). The ability of polyP to enhance clot turbidity requires the presence of calcium ions (FIG. **8**). Furthermore, the effect of polyP on final clot turbidity is maximal when polyP has been preincubated for at least 15 minutes with fibrinogen and calcium ions prior to initiating clot formation with thrombin (FIG. **4**).

It has been found that polyP increases the thickness of the fibrin fibrils. Previous studies of fibrin clot structure have shown that the final optical density of fibrin clots is primarily a function of the thickness of the fibrils formed [25]. It is possible to estimate the mass-length ratios of fibrin fibrils by measuring the optical density of clots at a series of wavelengths of light, using a suitable mathematical analysis of the data [22, 25]. Such analyses of fibrin clots were made by mixing fibrinogen and thrombin in the presence of calcium ions and varying concentrations of polyP, in order to determine the effect of polyP on the mass-length ratio of the fibrils (FIG. **5**(A)). These analyses demonstrated that the fibrin fibrils had mass-length ratios that were more than three times larger when clots were made in the presence of 1 mM polyP, compared to fibrin clots formed in the absence of polyP. When fibrin clots formed in the presence of calcium ions and varying polyP concentrations were visualized using scanning electron microscopy, the fibrin fibrils had increased thickness as the polyP concentration increased (FIGS. **5**(C-E)). When the fibrin fibril thickness was quantified from such electron micrographs, it was found that polyP resulted in substantially thicker fibrils (FIG. **5**(B)).

It should be pointed out that commercial preparations of purified fibrinogen typically contain traces of factor XIII. Therefore, it was conceivable that polyP could be influencing clot structure by modulating the rate or extent of covalent cross-links catalyzed by factor XIIIa. The effect of polyP on final clot turbidity does not appear to result from changing the rate or extent of fibrin cross-linking by factor XIIIa, however. This conclusion comes from studies in which iodoacetamide (a factor XIIIa inhibitor) was added to clotting mixtures to eliminate fibrin cross-linking by factor XIIIa. It was found that polyP enhanced final clot turbidity approximately equally well in the presence or absence of iodoacetamide (data not shown). In additional experiments, the extent of covalent fibrin cross-linking using SDS-PAGE was monitored. The rate of formation of cross-linked fibrin chains appeared to be the same with or without polyP (data not shown).

It was also found that fibrin clots that were made in the presence of polyP and calcium ions were more resistant to fibrinolysis than clots made in the absence of polyP. In these experiments, clots were formed by mixing purified human fibrinogen, human plasmin, and human thrombin in the presence of calcium ions, with or without polyP. Clot lysis was quantified by measuring the decrease in optical density over time (following a 30 minute initial clot formation). It was found that clots that had been prepared without polyP lysed quickly, while clots prepared with polyP were highly resistant to lysis by plasmin. (FIG. **6**)

In Vivo Results (Porcine Splenic Trauma Model)

In preliminary experiments, the ability of polyP to enhance the performance of a fibrin sealant composed of purified fibrinogen and thrombin was evaluated. The fibrinogen component of the experimental fibrin sealant was pre-mixed with calcium ions and polyP, while control fibrinogen preparations were pre-mixed with calcium ions without polyP. Shallow surface wounds were then made on the surface of the spleen of anesthetized pigs, after which 0.3 mL each of the fibrinogen and thrombin solutions were applied to the wound surface and allowed to react with each other. Including polyP in the fibrinogen solution shortened the time to cessation of bleeding in this model: 9.8±1.0 minutes with polyP, but 12.3±1.0 minutes without polyP (mean±SEM). Adding polyP to the fibrinogen solution also changed the appearance of fibrin clots formed on the wound surfaces. As can be seen in FIG. **7**, when the fibrinogen contained polyP (dark circles) the resulting fibrin seals were more opaque, and they mounded up to a greater degree over the wound surface than when fibrinogen did not contain polyP (white circles).

Methods

Purified human fibrinogen in 20 mM citrate pH 7.4 was from Enzyme Research Laboratories (South Bend, Ind.), as were human α thrombin, plasmin, and factor XIII. For some experiments, citrate was removed from fibrinogen immediately prior to use by rapid gel filtration of the fibrinogen solution on Econo-Pac 10DG desalting columns (Bio-Rad, Hercules, Calif.) equilibrated with TBS (50 mM Tris HCl, pH 7.4, 150 mM NaCl, 0.02% NaN3). Fibrinogen concentrations were determined by measuring A_{280}, using an extinction coefficient of 1.51 (1 cm path length) for a 1 mg/mL solution of fibrinogen. Unfractionated heparin and $polyP_{75}$, a polyP preparation containing a mean polymer size of approximately 75, were from Sigma Aldrich (St. Louis, Mo.). Concentrations of polyP are expressed in terms of phosphate monomer.

Measurements of Clot Turbidity

Fibrin clots were formed in 96-well polystyrene microplates (Corning Inc., Corning, N.Y.) by first preincubating fibrinogen with polyP in TBS plus the indicated $CaCl_2$ concentrations. (Preincubations of fibrinogen with calcium ions were for 15 minutes unless otherwise stated.) Thrombin in TBS plus the same concentration of $CaCl_2$ was then added to trigger clot formation. Reactant concentrations were typically 2.6 mg/mL fibrinogen, 62.5 pM to 8 nM thrombin, 0 to 8 mM polyP, and 0 to 5 mM $CaCl_2$ in a total volume of 200 μL. In some studies, 0 to 10 U/mL unfractionated heparin or 1 mM iodoacetamide were also included. Clotting was evaluated by monitoring the change in turbidity (A_{405}) for varying times (typically, 1 hour) at room temperature using a Spectramax microplate reader (Molecular Devices Corporation, Sunnyvale, Calif.). Clotting times were calculated from these data using SigmaPlot to fit a line to the steepest segment of the absorbance curves and then determining the intersection of this line with the initial baseline A_{405} (representing the lag phase prior to clot formation). Final turbidities (A_{405}) of fibrin clots were typically quantified after the clots had matured for 60 minutes.

Fibril Size Determination

Relative fibril mass to length ratios were determined using a modification [21] of the method of Carr and Gabriel [10] for clots with high turbidity. Briefly, fibrin clots were allowed to mature for 2 hours after thrombin addition, after which the absorbance was scanned from 400 to 800 nm on a Spectramax microplate reader. A plot of $1/\tau*\lambda^3$ (y axis) versus $1/\lambda^2$ (x axis) was used to determine the y intercept, the inverse of which is proportional to the mass-length ratio of the fibers [10]. Data were normalized in comparison to clots formed under identical conditions but in the absence of polyP, whose relative mass-length ratios were defined as 1.0 [22].

Scanning Electron Microscopy

Fibrin clots formed as described above for turbidity measurements were allowed to mature for 2 hours after thrombin addition. Clots were washed 4 times in 0.1 M cacodylate, fixed in Karnovsky's gluteraldehyde solution overnight, and then processed by stepwise ethanol gradient, critical point drying, and sputter coating with gold palladium. Clots were observed and photographed in six different representative areas using a scanning electron microscope.

Fibrin Cross-Link Formation

Rates of a and y cross-link formation were studied in clotting reactions carried out as described for turbidity measurements using purified fibrinogen, except that fibrin clots were formed in polypropylene tubes at 37° C. and reactions were stopped at various times by adding an equal volume of 2×SDS sample buffer (100 mM Tris-HCl, 1 mM dithiothreitol, 4% sodium dodecyl sulfate (SDS), 0.02% bromophenol blue, 20% glycerol, pH 6.8) with immediate boiling at 95° C. for 5 minutes. Samples (10 μL) were then subjected to SDS-PAGE using 7.5% polyacrylamide gels and stained with Gelcode (Pierce, Rockford, Ill.) according to the manufacturer's directions.

In Vivo Studies:

Young adult pigs weighing 20-35 kg were anesthetized using intramuscular teletamine/zolazepam/glycopyrolate, followed by intubation and maintenance with inhaled isoflurane. A ventral midline laparotomy was performed and the spleen was externalized. Shallow (approximately 1 mm deep) oval surface wounds measuring approximately 3×5 mm were made using a Metzenbaum scissors. The initial hemorrhage was blotted away to allow visualization, and then the fibrin sealant mixture was applied as follows: 0.3 mL of the fibrinogen solution (containing 33.6 mg/mL fibrinogen, 20 mM sodium citrate, 150 mM NaCl, 20 mM Hepes pH 7.4, 20 mM $CaCl_2$, with or without 100 μg/mL $polyP_{75}$) and 0.3 mL of the thrombin solution (containing 100 U/mL thrombin, 150 mM NaCl, 20 mM Hepes pH 7.4, 5 mM $CaCl_2$) were applied simultaneously to the wound surface using 1 cc syringes with attached 18 gauge needles. For some wounds a 10×10 mm piece of gelfoam was then applied to the wound surface immediately after applying the fibrin sealant mixture. Time to cessation of bleeding was assessed visually. The surgeons were blinded as to which preparations contained polyP, and the wound locations on the spleen were matched for fibrinogen preparations, so the wounds that received polyP were in the same location as wounds that did not. Animal studies were approved by the University of Illinois Institutional Animal Care and Use Committee.

In contrast to the lack of effect on thrombin clotting time, polyP markedly increased final clot turbidity. Clots formed in the presence of polyP were substantially more turbid than clots formed in the absence of polyP, regardless of the amount of thrombin added. Interestingly, the ability of polyP to modulate the turbidity of the resulting fibrin gel was dependent on the Ca^{2+} concentration. In the absence of Ca^{2+}, polyP did not increase the turbidity of fibrin clots, but at mM Ca^{2+} concentrations, adding polyP did increase the final turbidity of the fibrin clot (FIG. **8**). The polyP concentrations exerting maximal effects on turbidity varied depending on the Ca^{2+} concentration: 1 mM polyP at 2 mM Ca^{2+}, 1-2 mM polyP at 2.5 mM Ca^{2+}, 2-4 mM polyP at 3 mM Ca^{2+}, and 3-8 mM polyP at 5 mM Ca^{2+}.

Fibrinogen contains a heparin binding site [23] and heparin increases the turbidity of clots formed from purified fibrinogen and thrombin [24]. Since heparin and polyP are both negatively charged polymers, the turbidity of fibrin clots formed in the presence of polyP was directly compared with the turbidity of clots formed in the presence of heparin. Heparin increased fibrin turbidity in a dose-dependent fashion (examined from 0 to 10 units/mL), but the magnitude of the turbidity increase with heparin was markedly lower than that observed with polyP (data not shown). Further, addition of up to 20 U/mL of unfractionated heparin to reactions containing 500 μM polyP did not reduce the effect of polyP on turbidity. Rather, the mild increase in turbidity due to inclusion of heparin appeared to be additive to the effect of polyP (data not shown). These results suggest that the polyP effect on fibrin clot turbidity is distinct from that of heparin.

The ability of polyP to enhance fibrin clot turbidity required a time-dependent preincubation of fibrinogen, Ca^{2+} and polyP, and was maximal when the three were preincubated together for approximately 10 to 15 minutes (FIG. **4**).

Varying the order of addition of these components demonstrated that all three had to be present during the preincubation period in order to achieve maximal increases in clot turbidity (not shown).

The fact that polyP enhanced clot turbidity only in the presence of Ca^{2+} suggested that this enhancement might be associated with factor XIIIa cross-linking activity, which is also calcium-dependent. Since purified fibrinogen may contain small amounts of contaminating factor XIII, some degree of covalent crosslinking is likely to occur during the formation of fibrin gels. However, it was observed that polyP still increased fibrin clot turbidity when preactivated factor XIIIa was added to the clotting mixtures (data not shown). Furthermore, the transglutaminase inhibitor, iodoacetamide, failed to antagonize the enhancement of final clot turbidity by polyP (data not shown). Finally, SDS-PAGE analysis failed to identify any impact of polyP on the time-dependent disappearance of the fibrinogen y chain, or the appearance of γ-γ dimers or a polymers (data not shown). These results indicated that the increase in fibrin gel turbidity associated with polyP was not dependent on the cross-linking activity of factor XIIIa.

Representative images of fibrin clots made from purified fibrinogen, Ca^{2+} and thrombin (±polyP) are presented in FIGS. **5**(C), **5**(D), **5**(E) and **5**(F). Clots made in the presence of polyP had markedly thicker fibers than clots made without polyP. Mean fibril thickness (±standard error) for clots made in the absence of polyP was 26.5±0.7 nm. Mean fibril thicknesses for clots made in the presence of polyP were: 33.6±1.0 nm with 100 μM polyP; 54.2±1.3 nm with 500 μM polyP; and 73.4±1.5 nm with 1 mM polyP.

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What is claimed is:

1. A fibrin sealant composition, comprising:

(a) a first container containing a first composition comprising isolated or recombinant thrombin, and

(b) a second container containing a second composition comprising: purified or recombinant fibrinogen, polyphosphate (polyPn), wherein n is at least 25, and calcium.

2. The fibrin sealant composition of claim **1**, wherein n is 25-1000.

3. The fibrin sealant composition of claim **1**, further comprising a cross-linking agent.

4. The fibrin sealant composition of claim **3**, wherein the cross-linking agent is factor XIII.

5. The fibrin sealant composition of claim **1**, further comprising a fibrinolysis inhibitor.

6. The fibrin sealant composition of claim **1**, wherein the fibrinogen is present in an amount between 2.5 to 200 mg/mL.

7. A fibrin sealant kit, comprising:

(I) a first container containing a first composition comprising isolated or recombinant thrombin,

(II) a second container containing a second composition, stored separate from the first composition, comprising: purified or recombinant fibrinogen, polyphosphate (polyPn), wherein n is at least 25, and calcium, and

(III) a fibrin sealant applicator.

8. The fibrin sealant kit of claim **7**, wherein n is 25-1000.

9. The fibrin sealant kit of claim **7**, further comprising a cross-linking agent.

10. The fibrin sealant kit of claim **9**, wherein the cross-linking agent is factor XIII.

11. The fibrin sealant kit of claim **7**, further comprising a fibrinolysis inhibitor.

12. The fibrin sealant kit of claim **7**, wherein the fibrin sealant applicator is a double barreled syringe.

13. The fibrin sealant kit of claim **7**, wherein the fibrin sealant applicator is a spray applicator.

14. The fibrin sealant composition of claim **1**, wherein the fibrinogen is recombinant fibrinogen.

15. The fibrin sealant composition of claim **1**, wherein the first composition and second composition are liquid.

16. The fibrin sealant composition of claim **1**, wherein the fibrinogen, polyPn and calcium have been incubated for at least 15 minutes.

17. The fibrin sealant kit of claim **7**, wherein the fibrinogen is recombinant fibrinogen.

18. The fibrin sealant kit of claim **7**, wherein the first composition and second composition are liquid.

19. The fibrin sealant kit of claim **7**, wherein the fibrinogen, polyPn and calcium have been incubated for at least 15 minutes.

20. The fibrin sealant kit of claim **7**, wherein the fibrinogen is present in an amount between 2.5 to 200 mg/mL.

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