The Preclotting of Porous Arterial Prostheses

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A four-step preclotting method is presented for use with porous filamentous Dacron® prostheses in the fully-heparinized patient. The method employs controlled fibrin formation within graft interstices, heparin neutralization of all thrombin remaining in the graft wall, and delay of systemic heparin neutralization until 15–20 minutes after clamp release. The resulting flow surface is impervious, smooth and hypothrombogenic. Experimental data are presented which support the rationale of this four-step preclotting method. Four years of clinical experience with the method are summarized, involving 300 prosthesis limbs used in aortic bifurcation, aortofemoral, femorofemoral, axillary-femoral and femoropopliteal positions in 192 patients. A clinical perspective of preclotting techniques is presented in which the proper use of this new method is suggested.

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THE WALL OF AN ARTERIAL PROSTHESIS must be porous if the body is to heal it. But fabric prostheses porous enough to be healed will bleed excessively at operation unless the walls are rendered impervious by preclotting. "Preclotting" refers to the conversion of the porous wall of a fabric prosthesis into one which has been rendered impervious by reaction with blood. The preclotting process is absolutely essential if porous fabric prostheses are to be employed in heparinized patients. Preclotting is also important when such grafts are used in nonheparinized patients. In view of this, we find it surprising that little study has been given to the subject.[4,10,14,15,35]

Three methods of preclotting are in common clinical use today. The first method involves submersion of the prosthesis in a pan of blood where it is left until solid clotting occurs. In the second method, termed "*in situ*" preclotting, the graft is wetted with blood to initiate fibrin formation in the interstices. This partially preclotted graft is then anastomosed to the proximal host vessel after which the arterial clamp is intermittently opened, allowing blood to pulse into the graft, permeate the interstices and complete the preclotting process. The third method, a variant of the second, is to proceed as just described but without prior wetting of the prosthesis by blood. All these methods share three serious disadvantages: none makes the graft adequately impervious for use in the fully-heparinized patient, the flow surface of the graft is not necessarily made smooth, and this surface is highly thrombogenic.

Because of dissatisfaction with these limitations we developed a preclotting method to eliminate them. It has four key steps and is termed the "four-step preclotting method." This technique was evolved during the period 1968–1973. It has been used in standardized form since January, 1974, and has been proven to give a flow surface that is impervious, smooth and hypothrombogenic. This method has permitted us to use the USCI® Sauvage ™ Filamentous Vascular Prosthesis*[26–32,36] safely in the fully-heparinized patient. In addition, as the graft is impervious, we can delay neutralization of heparin with protamine sulfate for 15–20 minutes after the clamps have been removed and full flow established. We delay administration of protamine sulfate because our experimental studies (*vide infra*) show that this delay in heparin neutralization significantly improves the one week patency rate of 4 mm prosthetic grafts of this type* in the canine carotid artery.

In this paper we describe the four-step preclotting method, present pertinent experimental and clinical data, and offer a clinical perspective of preclotting which we hope will be useful to the clinical surgeon.

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* The USCI® Sauvage ™ Filamentous Vascular Prosthesis (USCI, A Division of C. R. Bard, Inc., Billerica, Massachusetts), constructed of fully-texturized Dacron® yarn, is a highly porous graft to which a velour component has been added, giving full-wall filamentousness of a differential degree, maximal outside and minimal inside. The prosthesis has a wall thickness including the velour of 0.5 mm and has a water porosity averaging approximately 2,000 ml/cm²/min at 120 mm Hg.

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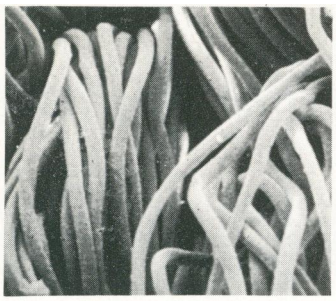
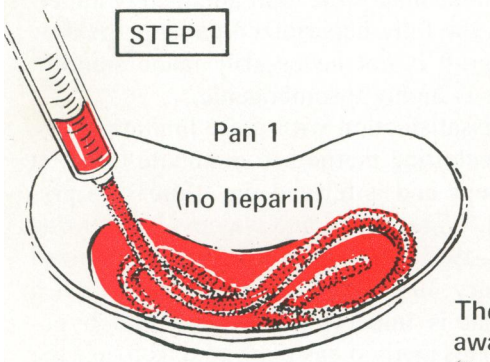


SCANNING ELECTRON MICROPHOTOGRAPH (SEM) of USCI® SAUVAGE™ FILAMENTOUS VASCULAR PROSTHESIS, x200.
Inner surface of virgin prosthesis before preclotting.

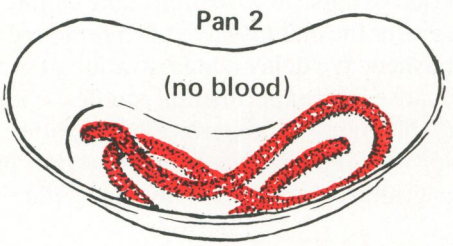
FOUR-STEP PRECLOTTING METHOD

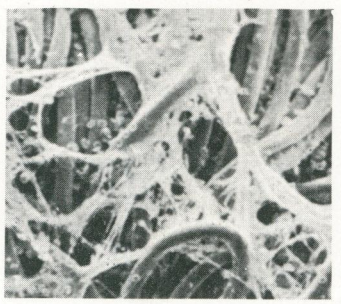
To avoid repeated venipunctures, insert needle with attached stopcock into vein in operative field. Withdraw blood (non-heparinized) as needed, 20-30 ml for a 75 cm x 8 mm graft, larger volumes for larger grafts. It is important to leave some blood in Pan 1 after the graft is transferred to Pan 2. If, like a sponge, the graft has soaked up all the blood, it will not be possible to visually confirm that clotting has occurred in STEP 1. Use a new syringe for each withdrawal of blood.



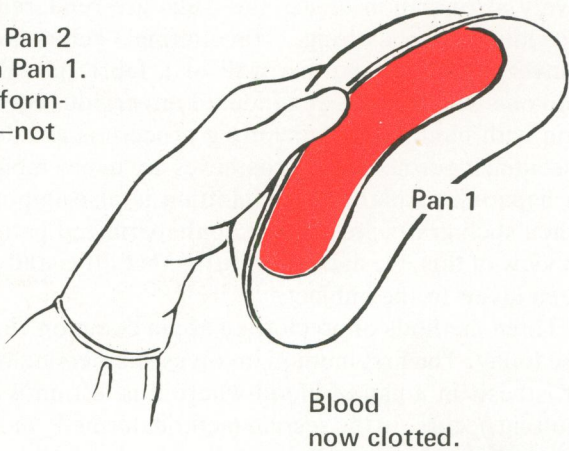
Wet graft in Pan 1 by injecting blood into lumen. After 2-3 minutes, remove the wet graft, stretch and place it in clean Pan 2.

The blood-soaked graft in Pan 2 awaits clotting of blood in Pan 1. During this time, fibrin is forming in the graft interstices—not in the lumen.





SEM of flow surface, x200



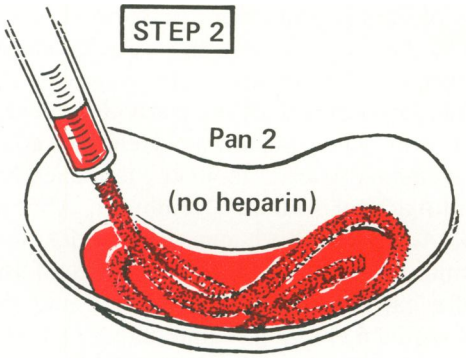
Blood now clotted. Thrombin present. Graft now ready for STEP 2.

CAUTION:

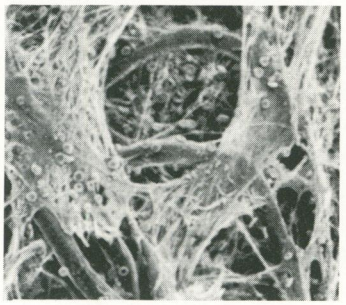
Should clotting fail to occur in Pan 1 after 7-8 minutes, repeat STEP 1. If clotting still fails to occur, add Thrombin, Topical. As thrombin will cause rapid clotting, quickly remove excess blood from graft with sponge to avoid intraluminal clotting.

FIG. 1. The Four-Step Preclotting Method: instructions on the sequential steps to be followed in preclotting a porous fabric prosthesis (USCI® Sauvage ™ Vascular Prosthesis) before giving systemic heparin. Scanning electron micrographs of graft flow surface illustrate appearances of the virgin graft and the same graft after each of the four steps.

STEP 2

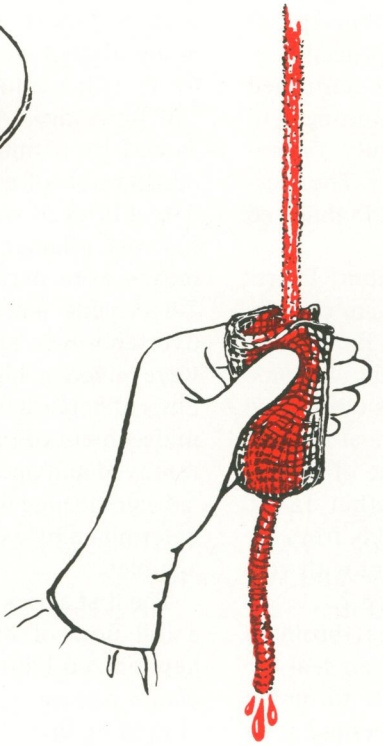


Inject another 20 ml of blood, but limit exposure to 20-30 seconds.

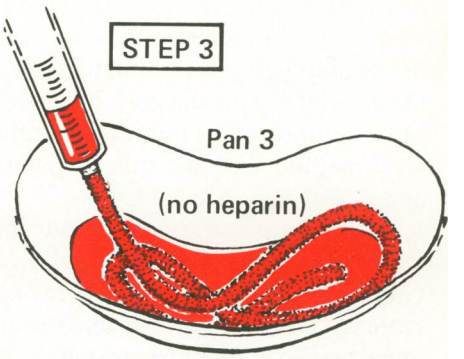


SEM of flow surface, x200

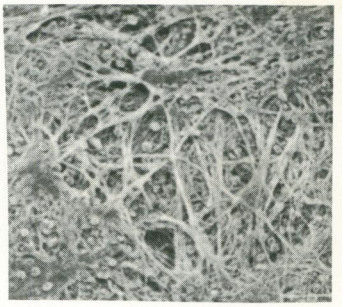
Strip excess blood from graft with sponge after blood injection in both STEPS 2 and 3.



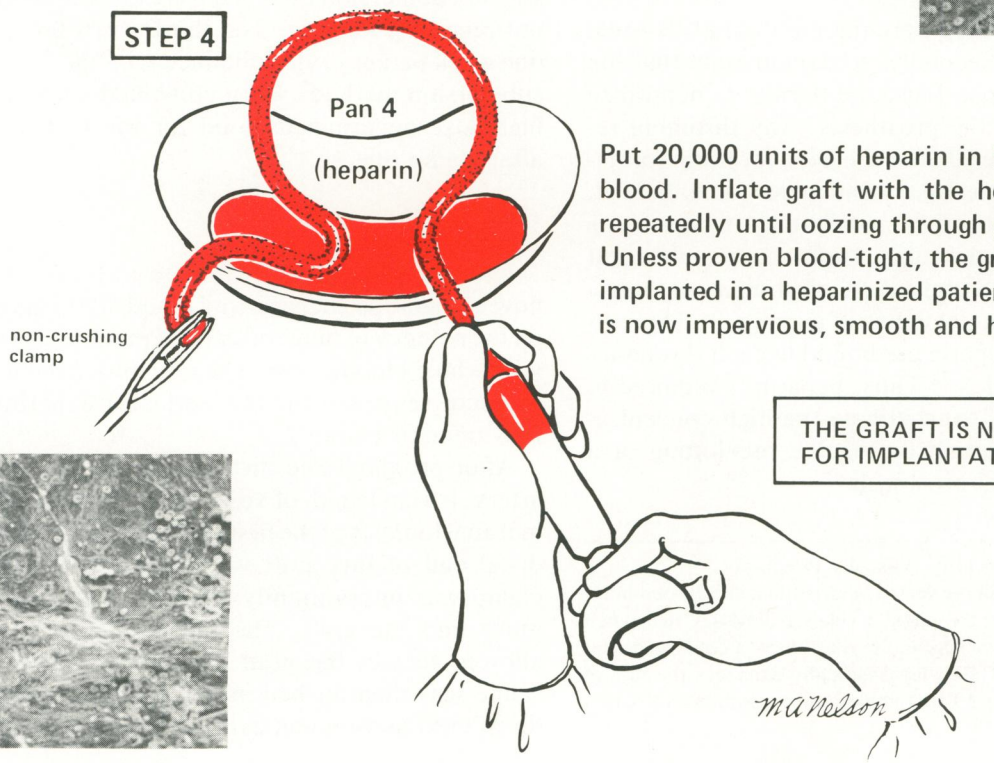
STEP 3



Inject another 20 ml of blood, but limit exposure to 10-15 seconds.



STEP 4



Put 20,000 units of heparin in Pan 4. Add 50 ml blood. Inflate graft with the heparinized blood repeatedly until oozing through graft wall has ceased. Unless proven blood-tight, the graft should not be implanted in a heparinized patient. The flow surface is now impervious, smooth and hypothrombogenic.

THE GRAFT IS NOW READY FOR IMPLANTATION

SEM of flow surface, x200

If there is concern that intraluminal fibrin septa may have formed in the graft, pull an inflated Fogarty embolectomy catheter through the graft.

The Four-step Preclotting Method

This four-step method systematically exploits the reaction between thrombin and fibrinogen to render a porous prosthesis* suitable for use in the fully-heparinized patient. To insure precise execution of the technique, it is designed to give the surgeon visual proof of proper completion of each step before proceeding. The four-step method entails repeated and controlled use of autologous thrombin to polymerize fibrinogen to fibrin, which seals the graft interstices. Finally, thrombin is neutralized by interaction with heparin. The four-step method and its salient points are emphasized and depicted in Figure 1.

The objective of Step 1 is to form thrombin. Therefore, it is absolutely essential for the surgeon to visually confirm that clotting has occurred in pan 1. Rarely, the patient's blood fails to clot and the graft cannot become impervious. In that circumstance, Step 1 is completed by adding a few drops of Thrombin, Topical (Parke-Davis, 1000 units/ml) to the blood. The use of topical thrombin will cause clotting to occur within 15–30 seconds, so the blood must be stripped quickly from the prosthesis to avoid intraluminal clotting. But with visible clot in pan 1, the graft is ready for Step 2.

The objective of Step 2, which utilizes thrombin generated in Step 1, is to form fibrin that can seal the graft interstices. Similarly, Step 3 utilizes thrombin from both Steps 1 and 2 with clotting proceeding at an accelerating rate because of increasing concentrations of thrombin.

The objectives of Step 4 are threefold: firstly, to seal tiny residual leaks; secondly, to demonstrate that the wall has become impervious; and thirdly, to neutralize all thrombin within the prosthesis. Any thrombin remaining in the graft wall after the need for fibrin formation has passed is unnecessary and undesirable. Indeed, graft thrombogenicity is not attributable to fibrin *per se*[21] but to persisting thrombin. Heparin, the only agent suitable for clinical neutralization of thrombin, interacts with thrombin in a stoichiometric manner.[24]† Three to four molecules of heparin are bound in each thrombin-anti-thrombin complex.[18] Thus, heparin is required in huge concentrations to inactivate the high concentration of thrombin formed during the preclotting of a porous fabric arterial prosthesis.

Experimental Data

Three series of experiments were performed in the carotid artery of the dog to assess the value of short-term heparin usage and to compare the values of the submersion and four-step preclotting methods with and without short-term heparinization. Healthy adult mongrel dogs weighing from 25 to 40 kg were anesthetized with pentobarbital sodium (Nembutal, Abbott, 100 units/mg). Access to both carotid arteries was gained by a midline incision. A 6 cm length of the mid-portion of a carotid artery was resected and the defect bridged with a 6 cm long, 4 mm diameter USCI Sauvage Filamentous Vascular Prosthesis. The anastomoses were performed in a continuous fashion using 7-0 Prolene placed either as an everting mattress or over-and-over suture. Seven days later the animals were given a high dose of pentobarbital and 10,000 units of heparin intravenously, and then sacrificed. The midsegment of the carotid artery bearing the graft was removed and opened to ascertain patency. The statistical significance of the patency rates within a series was determined by a chi-square distribution for independent samples.

The first series of experiments examined the effect of a full flow of high-dose (220 units/kg body weight) heparinized blood limited to the first 20 minutes after clamp release on the one week patency of grafts preclotted by the *in situ* method. In the second series, the one week patency rates of grafts preclotted by the four-step or submersion methods were compared in animals not receiving heparin. The third series compared the one week patency rates obtained with the four-step and submersion methods when combined with full flow of high-dose heparinized blood for the first 20 minutes after clamp release.

Series 1

Influence of an initial 20 minute graft exposure to full flow of high-dose heparinized blood after clamp release on the patency of bilateral carotid prostheses preclotted with whole blood *in situ*. The preclotting technique and protocol sequence for this series of experiments are illustrated in Figure 2.

After proximal and distal clamping of each carotid artery, a 6 cm length of vessel was resected. The proximal anastomosis of the first graft was performed and the distal end of this graft was occluded. The proximal clamp was intermittently released, allowing blood to pulse into the graft. The initial burst of blood was allowed to wet the graft for three minutes. Normal saline was then flushed into the graft lumen from the distal end. Subsequent exposures of the graft to blood

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* USCI Sauvage Filamentous Vascular Prosthesis.

† Thrombin inactivation is effected *in vivo* when anti-thrombin III (AT III) complexes with thrombin. Evidence indicates that when heparin binds to AT III via specific lysyl residues, a conformational change occurs in the AT III which markedly enhances the rate of formation of the thrombin-AT III complex and concomitant thrombin inactivation.[24,25]

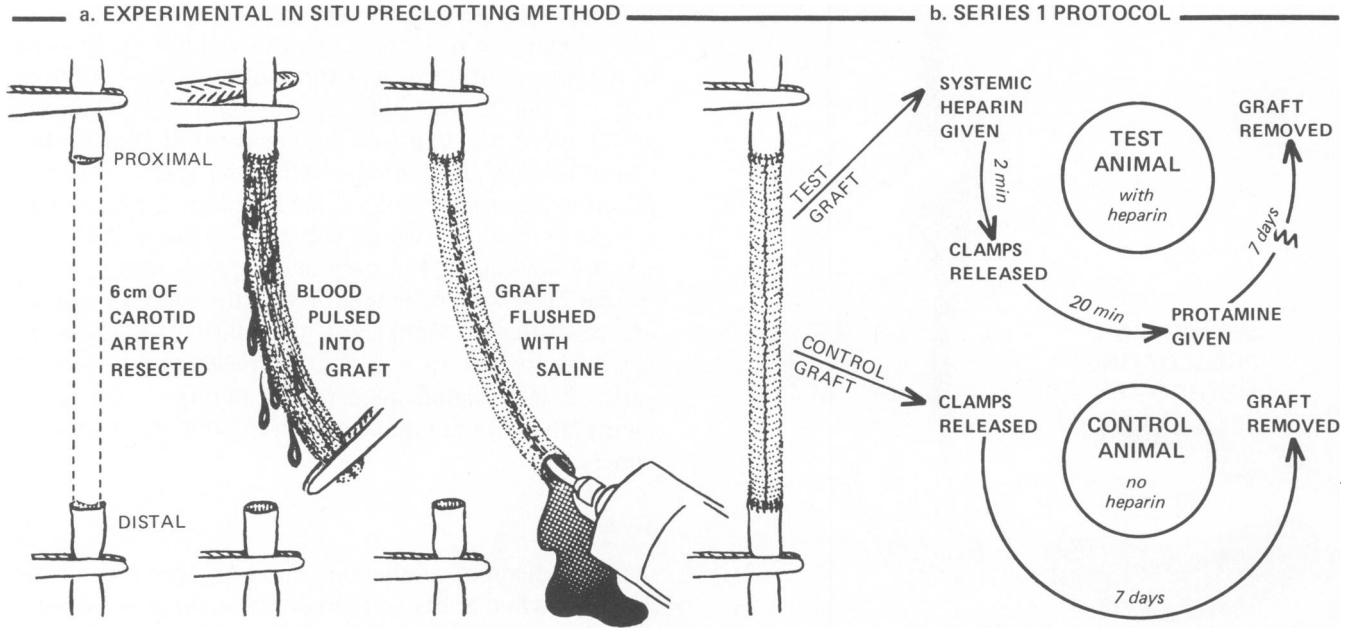

FIG. 2. Methodology of Experimental Series I. (a) *In situ* preclotting of prosthesis implanted in the canine carotid artery. (b) Protocol sequence for test (with heparin) and control (without heparin) group of animals.

were limited to 15–30 seconds to minimize intraluminal clotting caused by rapidly accelerating flow surface thrombogenicity. This process was continued until the graft wall became impervious. The graft was flushed thoroughly with saline to remove intraluminal clot; then the distal anastomosis was performed. The second graft was implanted in the opposite carotid in an identical manner.

In test animals 220 units heparin/kg body weight (Upjohn, beef lung, 1,000 units/ml) were administered intravenously and allowed to circulate for two minutes before simultaneous release of clamps on both sides. Twenty minutes after clamp release 2.2 mg protamine sulfate/kg body weight (Lilly, 100 units/mg) were administered intravenously at a rate of 10 mg/min. Control animals received neither heparin nor protamine sulfate. In general, test and control studies were performed alternately.

Three identical sets of experiments, each involving 10 animals (sets A, B and C), were performed in this series. These studies were conducted intermittently over a 17 month period. Each animal received bilateral grafts. Hence, each set of ten animals comprised five receiving ten test grafts and five receiving ten control grafts.

The patency results from these three sets of experiments are shown in Table 1. In each of the three sets of studies, seven day patency was increased from 20%

TABLE 1. *Effect of Full Flow of High-Dose Heparinized Blood for the First 20 Minutes after Clamp Release on 7-Day Patency of Filamentous Dacron Prostheses Preclotted by an* in Situ *Method and Implanted in Canine Carotid Artery*

	Type of Experiment	Number of Grafts	Number of Dogs	Number Patent	Percentage Patent*
Set A	Systemic heparin flow for 20 minutes	10	5	7	70
	No systemic heparin	10	5	2	20
Set B	Systemic heparin flow for 20 minutes	10	5	7	70
	No systemic heparin	10	5	2	20
Set C	Systemic heparin flow for 20 minutes	10	5	7	70
	No systemic heparin	10	5	2	20
Totals	Systemic heparin flow for 20 minutes	30	15	21	70
	No systemic heparin	30	15	6	20

* These percentage patency differences are statistically significant ($p < 0.01$).

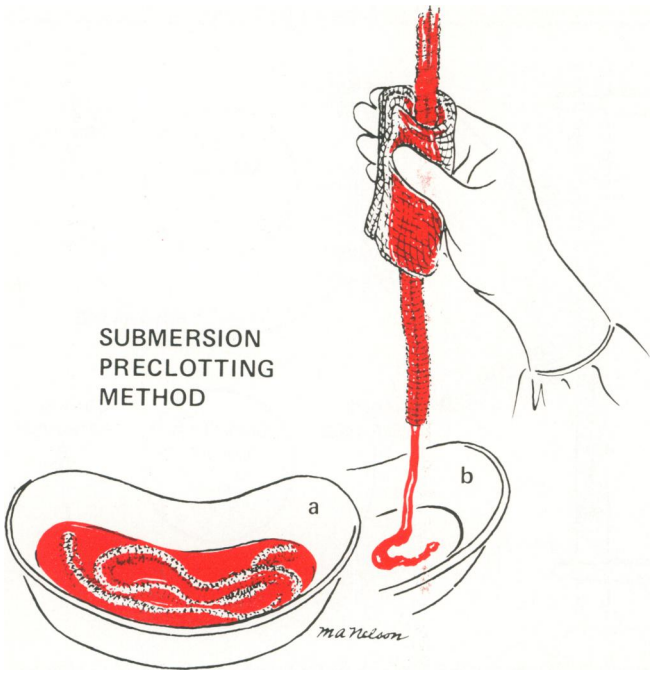

FIG. 3. The Submersion Preclotting Method: (a) Graft immersed in autologous whole blood until solid clotting occurs. (b) Graft stripped to remove clot.

(2 of 10) to 70% (7 of 10) by the high flow of heparinized blood for 20 minutes after clamp release. This improvement in patency is statistically significant ($p < 0.01$).

Series 2

Comparison of submersion and four-step preclotting methods when grafts were not exposed to heparinized blood after clamp release. The submersion preclotting method entailed graft immersion in autologous whole blood until solid clotting occurred (Fig. 3). The graft was stripped to remove clot. A 6 cm length was then used to bridge the carotid artery defect. Five grafts were implanted unilaterally using the right and left sides in alternate animals. The four-step preclotting method was employed for an additional five grafts which were implanted in an identical manner in alternate animals. Heparin was not given to any of these animals. The patency results are shown in Table 2. The patency of the submersion series was one of five (20%) while that of the four-step series was three of five (60%). In both series 1 and 2, graft patency was only 20% when the grafts were not exposed to heparinized blood after clamp release. In contrast, when the grafts were exposed to heparinized blood for 20 minutes after clamp release (series 1), 70% of the grafts were patent, and when it was employed only in the preclotting process (series 2) 60% were patent. While the data of series 1 are statistically significant ($p < 0.01$) the data of series 2 are not ($p > 0.10$). Although the results of series 2 lack significance (small numbers of experiments) they are compatible with the results of series 1 and 3.

Series 3

Comparison of submersion and four-step preclotting methods when grafts were exposed to full flow of high-dose heparinized blood for the first 20 minutes after clamp release.

The four-step preclotting method was employed to prepare ten grafts that were implanted in ten animals. After completion of anastomoses, 220 units heparin/kg body weight were administered intravenously and allowed to circulate for two minutes before clamp release. Twenty minutes after clamp release 2.2 mg protamine sulfate/kg body weight were administered intravenously at a rate of 10 mg/min. Ten grafts were preclotted by the submersion method and implanted in ten animals that received heparin and protamine sulfate in an identical manner. The patency results are shown in Table 3. All grafts (10 of 10) prepared by the four-step method plus systemic heparin for the first 20 minutes after clamp release remained patent. In contrast, only four of ten grafts prepared by the submersion method plus systemic heparin for the first 20 minutes after clamp release remained patent ($p < 0.05$). These results indicate that the attainment of flow surface hypothrombogenicity in preclotting is important and that exposure to short-term systemic heparin confers additional benefit.

TABLE 2. *Effect of Preclotting Method (Submersion vs Four-Step) on 7-Day Patency of Filamentous Dacron Prostheses Implanted in Canine Carotid Artery, When Grafts Not Exposed to Heparinized Blood*

Preclotting Method	Number of Grafts	Number of Dogs	Number Patent	Percentage Patent*
Submersion	5	5	1	20
Four-step	5	5	3	60

* These percentage patency differences are not statistically significant ($p > 0.10$).

TABLE 3. *Effect of Full Flow of High-Dose Heparinized Blood for the First 20 Minutes on 7-Day Patency of Filamentous Dacron Prostheses Preclotted by Submersion or Four-Step Method, and Implanted in Canine Carotid Artery*

Preclotting Method	Number of Grafts	Number of Dogs	Number Patent	Percentage Patent*
Submersion	10	10	4	40
Four-step	10	10	10	100

* These percentage patency differences are not statistically significant ($p < 0.05$).

Clinical Experience

The evolutionary development of the four-step preclotting method (Fig. 1) was complete by the end of 1973, and it has been used in standardized form since January, 1974. Reported herein are the results obtained in a consecutive series of 192 patients receiving USCI Sauvage Filamentous Vascular Prostheses preclotted by this method during the three year period January 1, 1974 through December 31, 1976 and followed through December 31, 1977. All grafts were implanted in fully-heparinized patients (200 units/kg body weight) with delay of protamine sulfate administration for 15–20 minutes after clamp release. This experience embodies five major categories of graft procedures: aortic bifurcation replacement after aneurysmectomy, aortofemoral bypass, femorofemoral crossover, axillary–femoral bypass and femoropopliteal bypass.

These 192 patients received a total of 300 graft limbs. For statistical purposes each limb of an aortic bifurcation graft, of an aorto-bilateral-femoral bypass and of a unilateral-axillary-bilateral-femoral bypass has been counted as a separate prosthesis. Mean implant time for the 300 grafts was 24.5 months. A total of 284 grafts remained patent while 16 closed. Patency for all implant sites was 94.7% with a range from 76.2% to 100%. Our four-year patency results obtained in the five main graft categories reported in life-table form (Figs. 4–8) are 100% patency for aortic bifurcation replacement, 100% for aortofemoral bypass, 93.5% for femorofemoral crossover, 81.8% for axillary-femoral bypass, and 66.1% for femoropopliteal bypass.

AORTIC BIFURCATION REPLACEMENT

patients	graft limbs	mean implant time	closures	patency
53	106	25.5 months	0	100%

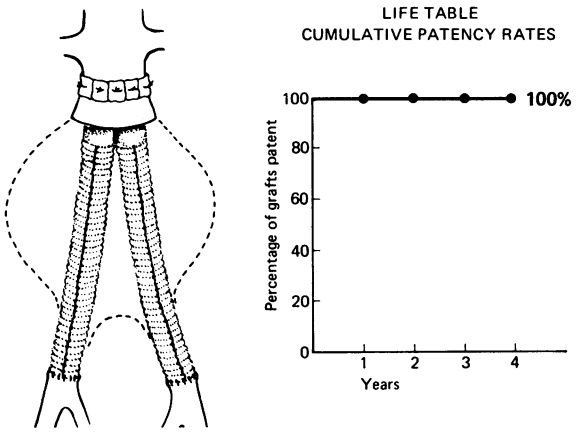

FIG. 4. A total of 106 aortic bifurcation limbs were implanted in 53 patients for an average of 25.5 months without any closures. These results compare favorably with published series.[11]

AORTOFEMORAL BYPASS

patients	graft limbs	mean implant time	closures	patency
42	84	25.6 months	0	100%

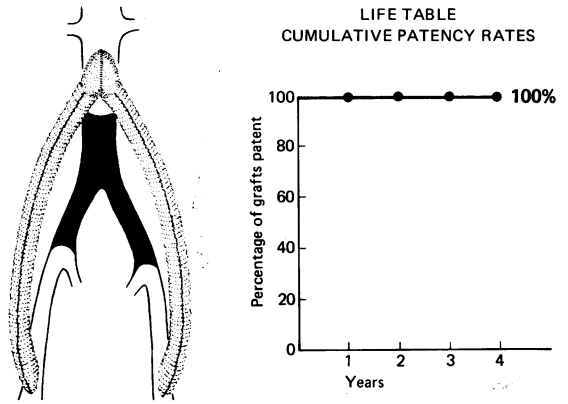

FIG. 5. A total of 84 aortofemoral graft limbs were implanted in 42 patients for an average of 25.6 months without any closures. These results compare favorably with published series.[11,16,17,19,22]

Clinical Perspective

The choice of preclotting technique in different circumstances for various procedures requires consideration of the advantages and disadvantages of each method. Table 4 summarizes the qualities of the four techniques available and presents our indications for their use.

Given a particular clinical situation, the surgeon must answer four questions. 1) What kind of graft should be employed? 2) If a porous graft is chosen, how should it be preclotted? 3) Should heparin be administered to the

FEMOROFEMORAL CROSSOVER BYPASS

patients	grafts	mean implant time	closures	patency
39	39	25.3 months	2	94.9%

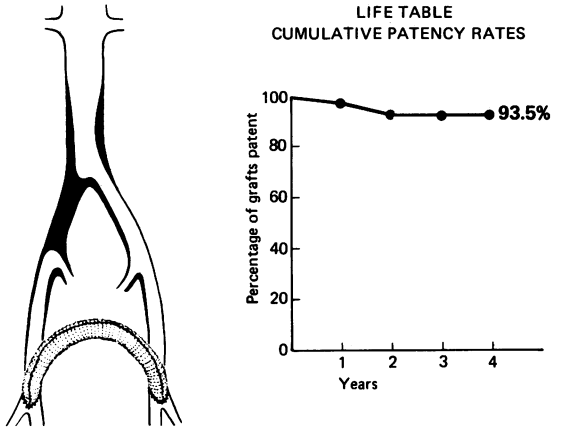

FIG. 6. A total of 39 femorofemoral crossover grafts were implanted in 39 patients for an average of 25.3 months with two closures. The patency rates compare favorably with published series.[1,12,23]

AXILLARY-FEMORAL BYPASS

patients	graft limbs	mean implant time	closures	patency
22	29	18.8 months	4	86.2%

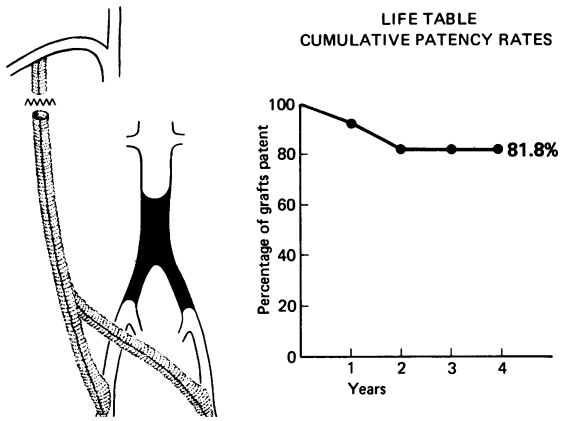

FIG 7. A total of 29 axillary-femoral graft limbs were implanted in 22 patients for an average of 18.8 months with four limb closures. The patency rates compare favorably with published series.[12,16,20]

patient? 4) If heparin is to be employed, should it be given systemically or only locally into the distal bed, and in what dosage?

We employ tightly woven prostheses for the ascending aorta and for dissecting aneurysms. Otherwise, the filamentous vascular prosthesis previously mentioned is used because of its better suturability and healing in comparison to woven prostheses. In addition, we believe that the preclotting and healing characteristics of this prosthesis are superior to other types of knitted prostheses. We employ the four-step preclotting technique in all clinical situations where this porous graft is used except in certain situations (*vide infra*) where large caliber, straight grafts are employed.

When the circulation is surgically interrupted we believe that heparin should be administered to protect the distal bed from stasis-induced thrombosis. This can be done intravenously or by downstream arterial injection. In general, we favor the use of heparin given intravenously in a dosage of 200 units/kg body weight. The use of systemic heparin has four advantages. Firstly, it renders the flow surface hypothrombogenic. Secondly, it protects the distal bed from thrombus formation. Thirdly, systemic heparin prevents blood in the operative field from clotting, including that which may seep into the graft. And finally, delayed neutralization of systemic heparin for 15–20 minutes after clamp release exposes the flow surface to a full flow of blood that cannot react by clotting. Procoagulants are washed away during these protected minutes. Additionally, the flow surface may be rendered passive by deposition of a very thin coat of protein, perhaps albumin.[2]

These experimental data indicate that the combination of the four-step preclotting method with an initial 20 minute exposure to a full flow of high-dose heparinized blood (220 units/kg) produces a better flow surface than that obtained with any of the other methods we have tried. The favorable clinical results we have obtained with this combination suggest that these experimental data are transferable to man.

However, in some clinical situations the use of large quantities of systemic heparin (200 units/kg) increases bleeding in the operative field to such an extent as to jeopardize the patient. Under these circumstances distal bed heparin injection (50 units/kg) should be employed.

In general, distal bed heparinization is indicated for fragile, aged patients, for those with ruptured aneurysms and for those requiring extensive dissection. When the abdominal aorta must be resected but the bifurcation can be saved, we employ a straight graft and protect the distal bed by injecting heparinized saline into the common iliacs. In such patients we usually do not use the four-step method; instead, we employ the *in situ* method illustrated in Figure 9. We initiate preclotting by wetting the graft with blood *before* any heparin is given. Then, after the upper anastomosis is performed, the preclotting process is completed by intermittently opening the proximal clamp to pulse short bursts of blood into the graft. Since the entire inner surface of such a large straight graft can be easily visualized, one can remove excess thrombus which may have formed. While the flow surface of a prosthesis prepared in this manner is highly thrombo-

FEMOROPOPLITEAL BYPASS

patients	grafts	mean implant time	closures	patency
36	42	23.0 months	10	76.2%

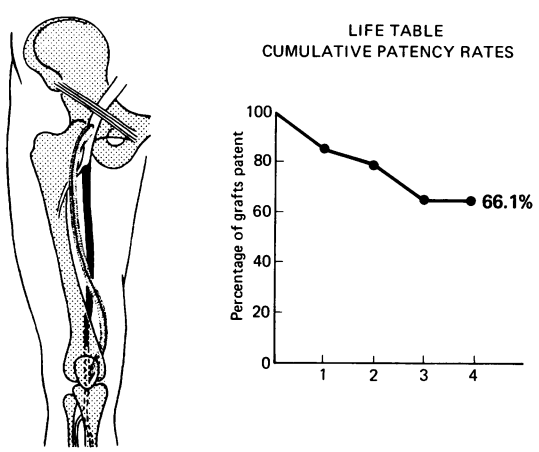

FIG. 8. A total of 42 femoropopliteal grafts were implanted in 36 patients for an average of 23.0 months with ten closures. The patency rates compare favorably with published series.[9,11,33]

TABLE 4. *Assessment of Preclotting Methods and Their Uses*

Preclotting Method	Feasible in Patient Given: A No Heparin	B Distal Bed Heparin	C Systemic Heparin	Preclotting Time	Blood Volume Required*	Graft Imperviousness	Flow Surface Smoothness	Thrombogenicity of Flow Surface	Applications and Indications for Use
1. Submersion	Yes	Yes	Unsafe	±10 min. for A and B; often no end point for C.	Variable; high if systemic heparin given	Variable	Variable	High	Limited value
2. *In situ*: Preliminary wetting with non-heparinized blood (see Fig. 9), followed by further exposure to blood after completion of proximal anastomosis	Yes	Yes	No	±3 min. for A and B; no end point for C.	Variable; may be very high if systemic heparin given	Variable	Variable	High	Straight, large caliber porous grafts when aortic bifurcation can be preserved and distal bed heparin employed. This technique (Fig. 9) is especially indicated in patients who (a) are frail or aged, (b) have a ruptured abdominal aneurysm, or (c) require extensive dissection
3. *In situ* variant: Exposure of dry graft to blood after completion of first anastomosis	Yes, but distal bed not protected	No	No	±10 min. for A; no end point for B and C.	May be very high; prohibitive if heparin given	Variable	Variable	High	Ill-advised
4. Four-step	Yes	Yes	Yes	15 min.	150 ml	Proven	Assured	Low	(a) all patients receiving porous grafts† in whom systemic heparin is used, (b) if distal bed heparin is employed the four-step method should be used if the flow surface cannot be visualized adequately as in long, small-caliber grafts†

* For an aortic bifurcation graft. † Our studies have been confined to the USCI® Sauvage™ Filamentous Vascular Prosthesis. The four-step preclotting method has not been evaluated with thin-walled, highly porous, non-filamentous fabric prostheses.

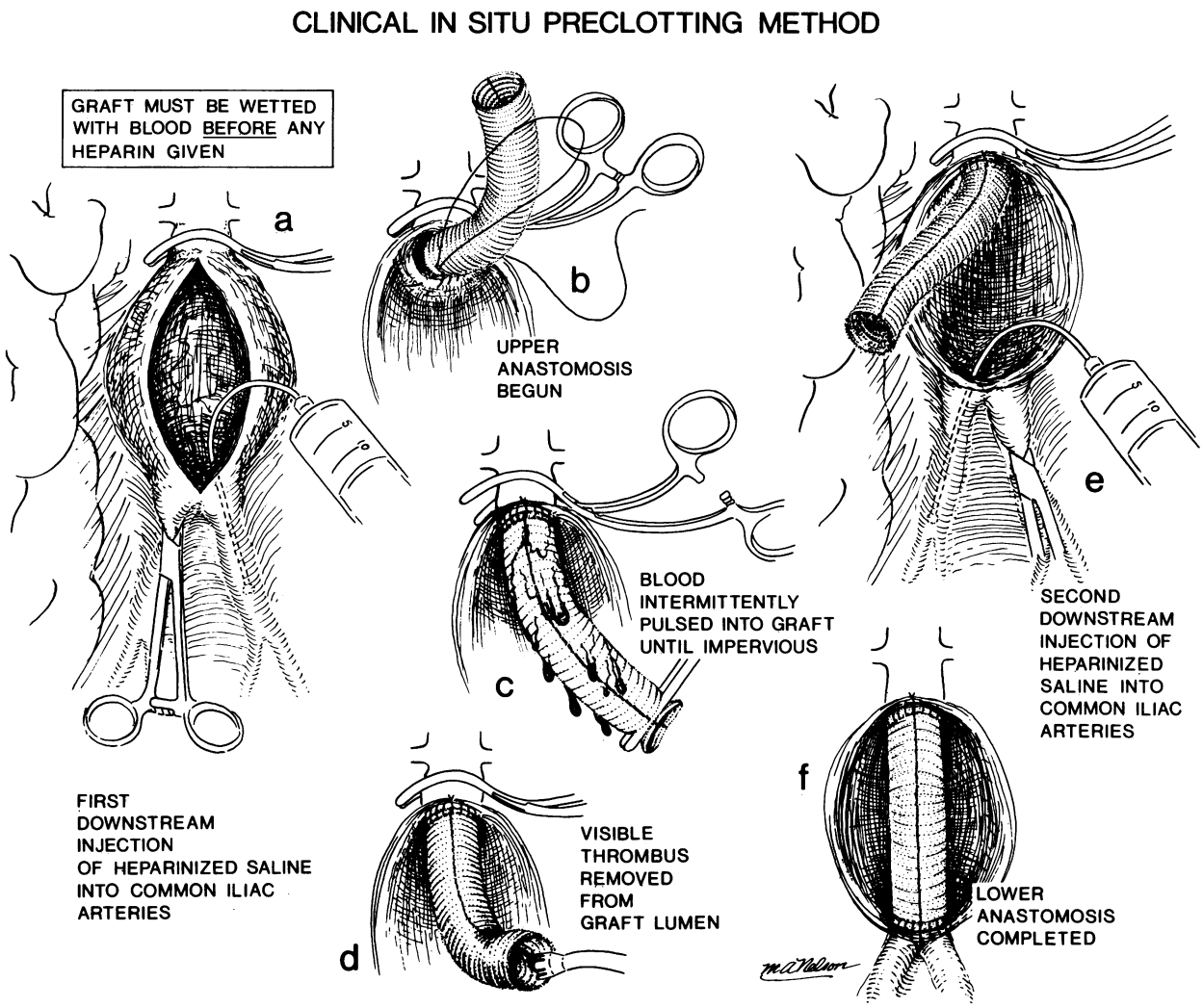

FIG. 9. Steps for *in situ* preclotting a straight graft when replacing abdominal aorta; distal bed protected by downstream injection of heparin into common iliacs. After the aneurysm is opened vertically, feasibility of preserving the bifurcation is assessed. If possible, it is saved and a straight graft is used. *Before* any heparin is given, the graft must be wetted with blood to initiate its preclotting. (a) After limited dissection, the infrarenal aorta and common iliac arteries are cross-clamped. Then the distal bed is heparinized by injecting 30 ml of heparinized saline into each common iliac (3,000 units heparin diluted in 100 ml normal saline). (b) After upper anastomosis is completed, graft is clamped distally (c) and the proximal clamp is released intermittently to pulse blood into the graft. Usually within two to three minutes the graft becomes blood-tight. As this occurs, the upper suture line can be checked and reinforced if needed. If the graft does not become blood-tight (an occurrence usually indicating failure to thoroughly wet the graft with blood before heparin was given, or that the graft was wetted with blood after the first distal bed heparin injection had been made) the inner surface of the graft should be bathed with a solution of Thrombin, Topical, and blood again pulsed into the graft to complete the *in situ* preclotting process. The graft, now blood-tight, is cut to proper length. (d) any visible thrombus within the graft lumen is extracted by suction under direct vision. (e) The distal bed is infused once again with heparinized saline. (f) The lower anastomosis is completed, after which the graft is covered by overlapping the residual aneurysm wall about it.

genic, this adverse characteristic is not significant in a large caliber aortic graft exposed to high flow, often above 1,000 ml/min.

If one fails to expose the graft to blood before injecting heparin into the distal bed, effective preclotting will be impossible without the addition of exogenous thrombin, for even the small amounts of heparin that then enter the systemic circulation from the distal bed will prevent clotting. Without active thrombin, the conversion of fibrinogen to fibrin cannot occur. But if clotting has already commenced in the graft (as in Step 1 of the four-step preclotting method), the high concentration of thrombin in the graft wall will not only neutralize the low concentration of heparin in the systemic blood, but will be more than adequate to form the polymer fibrin from fibrinogen and complete the preclotting process.

Caution is expressed against the use of the *in situ* preclotting method if the graft is long (aortofemoral) or of a caliber too small to permit adequate visualization of the entire flow surface. We recommend the four-step

preclotting method in all such instances. This insures that there will be no build-up of clot on the inner wall and no fibrin septa crossing the lumen (Fig. 10).

The principle that an ideal flow surface should be impervious, smooth and hypothrombogenic cannot be challenged on a logical basis. We consider such a flow surface essential for patency of prostheses in small arteries, and have previously reported the successful use of porous filamentous fabric grafts in the right coronary of two patients.[29,32] We believe that the four-step preclotting method with delayed neutralization of systemic heparin gave these coronary grafts excellent flow surfaces which contributed substantially to their success. However, further experimental data and clinical documentation will be necessary before this or any other type of prosthesis can be recommended for selected use in coronary bypass, especially for the left coronary system where the flow may completely stop in early systole.

The submersion and *in situ* methods of preclotting have been used successfully in the aortoiliac area in thousands of patients since prosthetic grafts were introduced by Voorhees and Blakemore in 1952.[34] We believe that these imprecise methods have enjoyed success in this area because of the large caliber of the vessels and the high flow through them (400–600 ml/min). Furthermore, we believe that the undesirable flow surface characteristics of porous fabric prostheses preclotted by conventional techniques are sufficient reason to explain the early closure of such grafts employed for femorotibial bypass.[13] As the vessel caliber decreases, the flow surface criteria for continued patency become increasingly demanding.

The importance of precise preclotting in attaining a uniformly high success rate with porous fabric prostheses, even in the aortoiliac area, is borne out by the experimental and clinical data presented in this paper. We suggest that precise preclotting is of great value in medium caliber vessels, and is essential if prostheses of this type are to be used in small caliber vessels.

In recent years significant advances have been made in the development of prostheses that do not need preclotting. Two of these—a nontextile Teflon prosthesis (GORE-TEX®)* and a glutaraldehyde-processed, externally-supported umbilical vein homograft (Meadox Biograft®)†—have been used clinically with considerable success for femorotibial bypass.[3,5–8] Currently it is thought that porous fabric prostheses cannot be used successfully for femorotibial bypass. However, the case against the use of such prostheses in this area is incomplete because only crimped prostheses have been employed and they have been preclotted by the imprecise submersion or *in situ* methods.

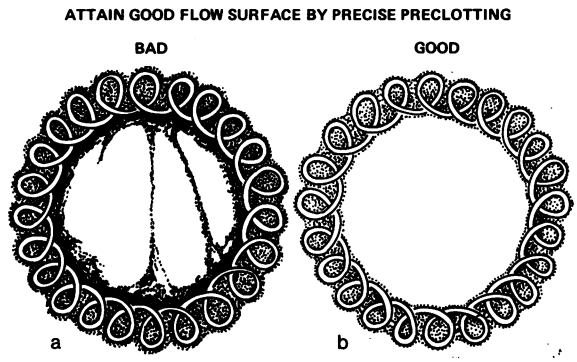

FIG. 10. Diagrammatic cross-section of preclotted grafts to show bad flow surface (a) and good flow surface (b). These results depend upon the preclotting technique employed. The bad flow surface is apt to occur if long or small-caliber grafts are preclotted by either the submersion or *in situ* methods. The figure illustrates the thick and irregular lining of thrombus with cross-channel fibrin septa which may form. The good flow surface should be routinely obtained for any length or caliber of graft if the four-step preclotting method shown in Figure 1 is performed accurately. The proper application of this method assures that the inner lining will be very thin and the flow surface impervious, smooth and hypothrombogenic.

Preliminary experimental data from this laboratory (to be published) show that a 4 mm diameter, *noncrimped*, porous filamentous Dacron® prosthesis prepared by the four-step preclotting method and an initial 20 minute exposure to full flow of heparinized blood has a substantially lower thrombotic threshold velocity (velocity at which thrombosis begins) in the canine carotid artery than the Biograft prosthesis. In contrast, the Gore-Tex prosthesis has a thrombotic threshold velocity comparable to that of the properly preclotted, noncrimped, porous, filamentous Dacron prosthesis. Additional unpublished findings show the seven day patency rate of the fabric prosthesis in the canine carotid artery has been higher than that of either the Gore-Tex or Biograft prostheses.

Summary

A new preclotting method is presented which reliably produces an impervious, smooth and hypothrombogenic flow surface in porous filamentous fabric prostheses. This method enables these prostheses to be used safely in fully-heparinized patients. It involves four steps and is moderately more complex than the submersion or *in situ* methods in common use. The flow surface of a prosthesis preclotted in this manner is further enhanced by exposure to full flow of high-dose heparinized blood for 15–20 minutes after clamp release. The advantages of this approach in terms of patency have been fully substantiated by the results of controlled

* GORE-TEX®, manufactured by W. L. Gore & Associates, Flagstaff, AZ.

† Biograft®, manufactured by Meadox Medicals, Oakland, NJ.

experimental studies and four years of clinical experience. We believe that the use of this preclotting method is of value even with large caliber porous filamentous fabric prostheses and is essential for those of small caliber.

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