IN VITRO AND IN VIVO EVALUATION OF NEW POLYESTER VASCULAR PROSTHESES

BY

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IN VITRO AND IN VIVO EVALUATION OF NEW POLYESTER VASCULAR PROSTHESES

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A Thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

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ABSTRACT

The purpose of this study was to evaluate the characteristics (textile, physical and chemical) of both virgin and explanted, unsealed and gelatin-sealed Twill Woven vascular prostheses (new prototype products under development by Vascutek Ltd., Inchinnan, Scotland, UK) and to compare these characteristics to those of commercially available prostheses which have proved to be successful in the past, with a view to determining the effect of the weave construction, the gelatin coating and the length of implantation on the performance characteristics of these two prostheses. The study was divided into two parts with the unsealed Twill Woven variety being the focus of the first part while the sealed variety constituted the second part. Standard procedures were used to evaluate the characteristics of the various prostheses and the data obtained were subjected to an analysis of variance to determine whether any significant differences existed in the performance characteristics of the prostheses.

The results of the study showed that the Twill Woven prostheses incorporated a modified plain woven construction with periodic warp floats. The sealed Twill Woven prosthesis differed from the unsealed variety only in having a gelatin coating. Nevertheless, both prostheses had excellent handling and suturing characteristics and with the exception of their water permeabilities, their performance characteristics did not differ significantly. The gelatin coating effectively reduced the water permeability of the Twill Woven prosthesis to zero so that preclotting was not required prior to implantation. Both prostheses had similar characteristics to those of the control prostheses but were statistically significantly different in their performance characteristics to those of the commercial prostheses used as controls. Despite the fact that statistical analyses could not be used to determine the effect of the length of implantation time on the performance characteristics of the Twill Woven prostheses, textile and thermal analyses indicated no changes in these properties as a result of implantation time.

ACKNOWLEDGEMENTS:

The author is indebted to (1) Dr. Martin King for his valuable help and guidance throughout the study (2) Dr. Robert Guidoin, Roshan Maini and Timothy Ashton for providing the prostheses and facilities for this study (3) Drs. Ann Macgregor and Bill Pelton for their helpful suggestions and (4) Xiaoyan Deng of the University of Laval who did some of the physical testing, Brigitta Badour of the University of Manitoba who performed the extractions, Jacques Bastien and Louisette Martin of the University of Laval who performed the implantations in animals, Yves Marois of the University of Laval for the histopathology studies and Gilles Mongrain (University of Laval), Suzanne Bourassa and Marielle Corriveau (Hospital St. Francois D'Assise, Quebec) for generating the photographs. I also wish to thank Mrs. Cecilia Gonzales for her moral support and encouragement.

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1. GENERAL INTRODUCTION AND LITERATURE REVIEW:

1.1. Introduction:

Vascular prostheses constructed from polyester fibres have proved to be the most reliable arterial substitutes for the replacement and bypass of diseased large and medium arteries. A number of different types containing either different textile constructions or different types of yarns have emerged over the years but the woven construction is preferred for the repair of abdominal aortic aneurysms[1] and for the replacement of the thoracic aorta because of its greater strength and superior ability to control blood loss[2,3]. The woven prosthesis is, however, more difficult to suture and handle and suffers from inferior healing[4,5] on account of poor attachment of the internal and external capsules to its smooth fabric surface[6].

To overcome these deficiencies, Vascutek Limited, a manufacturer of medical devices in Inchinnan, Scotland, UK, has recently developed a new prototype, Twill Woven prosthesis intended for use as an arterial substitute. Having a more open structure than the plain weave, the twill construction is expected to give a more flexible prosthesis which will also be easier to suture and handle. On the other hand, the prosthesis may have a reduced ability to control blood seepage, a condition which would require preclotting with the patient's blood prior to implantation and would increase the risk of infection. To eliminate this procedure, and to make the device suitable for implantation in diabetics and other patients with impaired blood properties, Vascutek has produced the sealed Twill Woven prosthesis by coating the surface of the unsealed Twill Woven prosthesis with gelatin, a resorbable, biological sealant, to render the prosthesis impermeable to blood and ready to implant without preclotting. The sealant is, however, expected to degrade slowly after implantation to allow for encapsulation of the prosthesis which would in turn encourage full wall healing.

The preceeding section describes some attractive features which

might prompt a surgeon to choose either the sealed or unsealed Twill Woven prosthesis as a replacement or bypass for a diseased artery. Prior to the general distribution of a new vascular prosthesis, however, a notice of compliance must be obtained from a regulatory agency (like the Bureau of Radioprotection and Medical Devices in Canada). These agencies recommend testing (in vitro and in vivo) of the new prosthesis to establish its merits. Such an evaluation will allow the forecasting of problems with certain types of devices and also provide explanations for differences in clinical performance of vascular prostheses[7].

1.1.1. Purpose of the study:

The purpose of this study was to evaluate the characteristics (textile, physical and chemical) of both virgin and explanted, unsealed and gelatin-sealed Twill Woven prototype prostheses and to compare these characteristics to those of commercially available prostheses. The first part of the study focussed on the unsealed Twill Woven prototype and the sealed variety formed the second part of the study.

1.1.2. The problem statements:

1. *What is the effect of weave construction on the performance characteristics of the virgin unsealed Twill Woven prosthesis?*
2. *What is the effect of the gelatin coating on the performance characteristics of the sealed Twill Woven prosthesis?*
3. *How do the performance characteristics of the explanted, unsealed Twill Woven prosthesis compare with those of the virgin unsealed Twill Woven prosthesis?*
4. *How do the performance characteristics of the explanted, sealed Twill Woven prosthesis compare with those of the virgin sealed Twill Woven prosthesis?*
5. *What is the effect of the nature of the sealant on the performance characteristics of different polyester prostheses?*

1.1.3. Hypotheses:

1. There is no significant difference between the performance characteristics of the Twill Woven prosthesis and other prostheses with different weave constructions.
2. There is no significant difference in the performance characteristics of the sealed and unsealed Twill Woven prostheses.
3. There is no significant difference between the performance characteristics of the sealed Twill Woven prosthesis and other sealed prostheses.
4. There is no significant difference in the performance characteristics of the virgin and explanted unsealed Twill Woven prostheses.
5. There is no significant difference in the performance characteristics of the virgin and explanted sealed Twill Woven prostheses.

1.1.4. Limitations of the study:

The first part of the study was limited to woven vascular prostheses. It is important to note that although textile characteristics like filament diameter, fabric count and yarn type are independent or extraneous variables, they could not be controlled in this study since the design of the vascular prostheses had already been established by the different manufacturers. The second part of the study was limited to gelatin and collagen coated prostheses. The fabric type, textile and yarn characteristics were not controlled in this study. In addition, the nature of the sealant, its method of preparation and other properties could not be controlled. Sampling was limited to one batch for each prosthesis. The University of Laval provided the explanted samples.

1.1.5. Definitions of terms:

Anastomosis: a connection between tubular structures or the surgical

formation of a channel between tubular structures, as blood vessels or intestines.

Aneurysm: a circumscribed sac-like bulging of a blood vessel, usually an artery.

Biocompatible: a biocompatible implant does not provoke an excessive or inappropriate response from the surrounding host tissue.

Capsule: a layer of new tissue, laid down by the body, surrounding an implant.

Embolism: the sudden blocking of an artery by a clot or a foreign material which has been brought to its site of lodgment by the blood current.

Heparinization: the process of rendering blood incoagulable with heparin (an acidic mucopolysaccharide present in many tissues especially the liver and lungs).

Preclotting: a procedure by which blood is allowed to penetrate and coagulate within the interstices of a porous prosthesis so as to decrease its porosity and render it impermeable to blood.

Performance characteristics: include water permeability, bursting strength, dilation (change in the prosthesis diameter at 120 mmHg pressure) and suture retention strength.

Porosity: the fraction of all the spaces, or voids to the total volume of the material. This property of a prosthesis is related to its healing capacity.

Pseudointima: (false) inner layer of a blood vessel.

Stenosis: abnormal constriction of a channel or an orifice.

Thrombosis: the formation or presence of a thrombus (a solid mass formed in the living heart or vessels from constituents of the blood).

Water permeability: the number of millilitres of filtered or distilled

water that passes through one square centimetre of a material per minute at a pressure head equivalent to 120 mmHg. This characteristic of a virgin prosthesis determines whether or not preclotting is required.

1.2. Literature review:

Vascular grafting as a surgical technique was pioneered by researchers like Jaboulay, Carrel, Pringle and many others[8]. A long period of time elapsed before Voorhees, Jaretzski and Blakemore[9] attempted the first constructive arterial surgery using Vinyon N prosthesis made from a commandeered US army air corps parachute. Since then, a large variety of synthetic fibres and structures have been evaluated for their biological response. Only polyethylene terephthalate (Dacron^R) and polytetrafluoroethylene (Teflon^R) were found to be sufficiently resistant to biodegradation to serve as useful prostheses[10]. Most commercially available synthetic fibre prostheses are made from Dacron^R polyester multifilament yarns fashioned into braided, woven or knitted structures.

Woven prostheses are dimensionally stable, exhibit a high bursting strength and a minimal tendency to fatigue, and can be woven tightly enough to allow minimal permeability to water and blood. They are preferred for use in high flow regions but are associated with poor healing characteristics due to their very low porosities. It has been suggested that low or non-porous materials prevent capillary ingrowth into the fabric interstices leading to a degeneration of the deepest layer of fibrin laid down on the luminal surface of the conduit[11]. In certain situations (e.g. full heparinization), only grafts with very low porosities can be used in order to avoid massive hemorrhage. Tightly woven taffetta type structures are known to have such low porosities.

Knitted prostheses, on the other hand, generally have high porosities which encourage capsular ingrowth and promote full wall healing. They are also easier to suture and handle but are not as strong

as the woven analogue and are not suitable for use in high flow regions because of their high water permeabilities and inability to control blood seepage. Various other types of polyester grafts, including compound grafts, have emerged over the years[12-14]. Compound grafts are composed of two or more integral substances one of which is resorbable by the body and another which is permanent. The rationale for the compound graft concept is to produce a prosthetic wall with a low porosity which controls blood loss at implantation, but with a significantly high healing capacity in the long term following resorption of the absorbable component[14].

Five classes of compound arterial prostheses may be currently available (coated mesh, pre-healed autogenized mesh, coated textile, compound textile and compound-yarn types)[14] but this review will be limited to studies on collagen and collagen-type coated textile prostheses. Earlier studies seemed to have indicated that these coatings decreased the effective healing capacity when compared with the uncoated material[15]. Some initial problems encountered with these sealants include cracking and peeling leading to unreliable porosity control; loss of handling characteristics; risk of embolism; interference with graft healing and acceleration of graft occlusion[16].

Recent studies[16-20], however, indicate that biological sealants can effectively control blood loss at implantation while maintaining a high healing capacity in the long run. Guidoin et al.[17] evaluated, in vivo, three commercial prostheses (the Hemashield®, The Tascon® Graft Bioprosthesis and the Gelseal®) by implanting these knitted and collagen-coated grafts as thoracoabdominal bypasses in dogs for periods of up to six months. They reported that the grafts did not require preclotting prior to implantation. In addition, no blood leakage was observed through the graft wall. All the dogs survived the implantation procedure and remained free from infection during the post implantation period. Neither thrombosis, obstruction nor anuerysm formation was observed at three and six months respectively. The three coated grafts showed different healing

properties from conventional preclotted prostheses but the coating did not interfere with their physical properties. The Gelseal impregnated with gelatin was found to be slightly better in this study than the bare analog in terms of the healing characteristics.

Jonas and his coworkers[21] assessed the biocompatibility and resorption of biomaterials used in sealing conduits by implanting subcutaneously, in weanling rats, a series of Dacron^R prostheses pretreated with either human albumin, freshly drawn human blood, autoclaved heparinized blood, fibrin glue, weakly cross-linked collagen or strongly cross-linked collagen. Their results showed that conventionally preclotted (e.g with human blood) prostheses had similar encapsulation and standard inflammatory response features to the bare analogue but the problem of haemorrhage could not be completely eliminated. Collagen impregnation, on the other hand, effectively controlled bleeding at implantation and also maintained a high healing capacity in the long run. The investigators noted that the specific methods of cross-linking were important in determining the histological reaction of the collagen, particularly the adhesion of the host inflammatory reactive tissue, and probably the rate of collagen resorption. Failure of the collagen to resorb because of excessive cross-linking produces an impervious conduit.

In another study, Jonas[22] assessed the healing characteristics of knitted Dacron^R conduits sealed with either fibrin glue, collagen cross-linked with glutaraldehyde or collagen cross-linked with formaldehyde by implanting them in the pulmonary and systemic circulatory systems of sheep and dogs for 3 and 6 months. The results of this study confirmed that delayed resorption of collagen cross-linked with either glutaraldehyde or formaldehyde resulted in lack of adhesion between inner capsule and conduit, thereby causing focal haemorrhagic dissection in the circulatory implants. These two studies[21,22] described above strongly suggest that the biological consequences of sealed grafts are strongly dependent on the

sealant material i.e. the nature as well as the method of preparation of the sealant. There was also some evidence to suggest that graft sealing with a substance that undergoes removal at a moderate rate is efficacious and safe.

Jonas[16] then extended these studies by examining weakly cross-linked gelatin as a new sealant for knitted Dacron^{R}. The gelatin was treated to reduce the number of free amino groups available for aldehyde cross-linking, a procedure resulting in weak cross-linking with an aldehyde mixture. This weakly cross-linked gelatin was applied to a knitted Dacron^{R} prosthesis which was then subjected to water permeability and implantation studies (subcutaneous in rat and canine circulatory). The permeability studies confirmed satisfactory control (7 ml min^{-1} cm^{-2} at 120 mmHg) and the implantation studies revealed relatively rapid and complete sealant resorption without undesirable modification of the normal healing process of knitted Dacron^{R}.

The effect of gelatin coating on the process of pseudointima biogenesis and inflammatory response has also been investigated[23]. This investigation was initiated by implanting three types of Dacron^{R} grafts (knitted crimped, knitted Gelseal and knitted noncrimped) as infrarenal aortic tube grafts, into six month-old mongrel puppies. The grafts, retrieved at two month intervals, were analyzed and the investigators found that the Gelseal did not hinder pseudointima formation nor did it induce local inflammatory response. Other investigators[24,25] have also failed to correlate Gelseal gelatin with enhancing inflammatory response. Harasaki and his coworkers[26] found, in their <u>in vitro</u> studies, neither thrombogenicity nor platelet adhesion associated with Gelseal and when compared with collagen, Gelseal gelatin has been shown[26-28] to degrade more rapidly. It has been suggested[16] that due to extensive processing, the bone derived bovine gelatin is highly water soluble and non antigenic. These properties prevent the gelatin from generating adequate local tissue reaction to induce inflammatory response (which can interfere with graft

incorporation).

In addition to the in vitro and animal studies reported above, Reigel et al.[29] have also implanted cross-linked, bovine collagen-impregnated, double velour, knitted aortic grafts in 590 humans (449 men and 141 women). They reviewed their experience with this graft over a two and half year period and reported that the graft was impervious to blood and maintained its pliability with use (characteristics not observed with standard knitted Dacron® prosthetic grafts in the aortic position). Seventy-nine percent of the patients experienced no perioperative complications. The remaining 21% had a variety of complications, most of them cardiac or pulmonary, but none related directly to the graft. Even though twenty-nine patients died in the perioperative period, the authors reported that no significant or unusual problems associated with the use of the graft were found. They observed that normal tissue ingrowth occurred and found no evidence of increased thrombogenicity. In addition, operative mortality, late mortality and late graft thrombosis were low.

From the discussion above, it is obvious that the ability of collagen and collagen-type biological sealants to function effectively depends on the nature and type of the sealant. In addition, the method of preparation of the sealant plays an important role in determining the rate of resorption of the sealant as well as the immunological response to the sealed prosthesis. The ideal vascular prosthesis[7] should be biocompatible, allowing healing with a nonthrombogenic surface and satisfactory incorporation with surrounding tissue. It should also be associated with a zero infection rate, be durable and strong, and last for the life expectancy of the patient. It should be easily handled and sutured and have a proven patency of 100% with no thromboses attributable to problems with the graft itself.

With these requirements in mind, the search for improved synthetic textile prostheses continues, and it is conceivable that in the future, new ones will appear with characteristics approaching the ideal

requirements. However, a note of caution may be useful in this context. Insistence on achieving an ideal graft may obscure the fact that the results of arterial grafting do not depend only on the type of vascular substitute but to a great extent on the status and progression of the arterial disease and upon the attention paid in applying the appropriate surgical techniques[30].

1.3. Research design:

1.3.1. General method:

An experimental-type approach was adopted. The type of woven construction, coating and implantation time were the independent variables while performance characteristics formed the dependent variables.

1.3.2. Sample:

In addition to the sealed and unsealed Twill Woven vascular prostheses, other commercially available prostheses were selected as controls. These prostheses are described in more detail in the appropriate section.

1.3.3. Experimental procedures:

Since there are two parts to this study, the specific procedures utilised for each part will be described in the appropriate section.

1.3.4. Treatment of the data:

The results are presented as means plus standard deviation in the tables and the error bars in the figures refer to half of the standard deviation. The data were subjected to one way analyses of variance to determine whether any significant differences existed in the performance characteristics of the prostheses being evaluated.

1.4. REFERENCES:

1. Eastcott H.H.G. An appraisal of the use and function of vascular grafts in England. In Vascular Grafts, P.N. Sawyer & M.J. Kaplitt (eds.), Appleton Century Crofts, New York, USA, 1978, pp 220 - 225.

2. Bloodwell R.D., Hallman G.L., Beall A.C., Cooley D.A. & DeBakey M.E. Aneurysms of the descending thoracic aorta: surgical consideration. Surg. Clinics. Ass. N. Am., 1966, 46: 901 - 911.

3. Pan C. & Rao T.J. Experimental research and clinical results of the local-made polyester arterial prosthesis. J. Jap. Soc. Chest Surg. 1982, 30: 43 - 50.

4. Callow A.D. Current status of vascular grafts. Surg. Clinics. Ass. N. Am., 1982, 62: 501 - 513.

5. Edwards W.S. Arterial grafts: past, present and future. Arch. Surg., 1978, 113: 1225 - 1233.

6. DeBakey M.E., Jordan G.I., Beall A.C., O'Neal R.M., Abbott J.P. & Halpert B. Basic biologic reactions to vascular grafts and prostheses. Surg. Clinics. Ass. N. Am., 1965, 45: 477 - 497.

7. National standard for vascular graft prostheses, ANSI AAMI VP20-1986. Association for the Advancement of Medical Instrumentation, Arlington, VA, USA.

8. Guidoin R., Couture T., Assayed F. & Gosselin C. New frontiers in vascular grafting. Int. Surg., 1988, 73: 241 - 249.

9. Voorhees A.B., Jaretzski A., & Blakemore A.H. The use of tubes constructed from Vinyon N cloth in bridging arterial defects. Ann. Surg., 1952, 135: 332 - 336.

10. Snyder R.W., Tenney B., & Guidoin R. Strength and endurance of vascular grafts. In H.E. Kambic, A. Kantrowitz & P. Sung (eds.), Vascular Grafts Update: Safety and Performance, ASTM STP 898, 1986, pp 108 - 121.

11. Wesolowski S.A., Fries C.C., Karlson K.E., DeBakey M.E. & Sawyer P.N. Porosity: primary determinant of ultimate fate of synthetic vascular grafts. Surgery, 1961, 50: 91 - 96.

12. Guidoin R., Snyder R.W., Awad A.J. & King M.W. Biostability of vascular prostheses. In Cardiovascular Biomaterials, G.W. Hastings (ed.), Springer-Verlag, London, 1992, pp 143 - 166.

13. King M.W. Designing fabrics for blood vessel replacement. Can. Text. J., 1991, 108: 24 - 30.

14. Wesolow A. Biologic behavior of tissue and prosthetic grafts. In Vascular Surgery: Principles and Techniques, H. Haimovici (ed.), Appleton-Century-Crofts, Norwalk, 1984, pp 93 - 118.

15. Wesolowski S.A., Fries C.C. & Komoto Y. Paper fabricated vascular prostheses: influence of wall thickness, compounding and coating upon healing. J. Cardiovasc. Surg., 1969, 10: 139 - 146.

16. Jonas R.A., Ziemer G., Schoen F.J., Lewis B., & Castaneda A.R. A new sealant for knitted Dacron^{R} prosthesis: minimally cross-linked gelatin. J. Vasc. Surg., 1988, 7: 414 - 419.

17. *Guidoin R., King M.W., Marceau D., Cardou A., De la Faye D., Legendre J.M. & Blais P. Textile arterial prosthesis: is water permeability equivalent to porosity. J. Biomed. Mater. Res., 1987, 21: 65 - 87.*

18. *Guidoin R., Marceau D., Couture, J., Rao T.J., Merhi Y., Roy P. & De la Faye D. Collagen coatings as biological sealants. Biomaterials, 1989, 10: 156 - 165.*

19. *Haverich A., Oelert H., Maatz W. & Borst H.G. Histopathologic evaluation of woven and knitted Dacron® grafts for right ventricular conduits: a comparative experimental study. Annals Thor. Surg., 1984, 37: 404 - 411.*

20. *Stratton J.W. & Hall R.V. Pseudointimal embolism from a woven Dacron® graft. Surgery, 1979, 86: 772 - 773.*

21. *Jonas R.A., Schoen F.J., Levy R.J. & Castaneda R.A. Biological sealants and knitted Dacron®: porosity and histological comparisons of vascular graft materials with and without collagen and fibrin glue pretreatments. Ann. Thor. Surg., 1986, 41: 657 - 663.*

22. *Jonas R.A., Schoen F.J., Ziemer G., Britton L. & Castaneda A.R. Sealants and knitted Dacron® conduits: comparison of collagen and fibrin glue pretreatments in circulatory models. Ann. Thor. Surg., 1987, 44: 283 - 290.*

23. *Sottiurai V.S., Sue S.L., Rau D.J., & Tran A.B. Comparative analysis of pseudointima biogenesis in Gelseal coated Dacron® knitted graft versus crimped and non crimped graft. J. Cardiovasc. Surg., 1989, 30: 902 - 909.*

24. *Vohra R. Drury J.K., Dhapiro D., Shenkin A. & Pollock J.G. Sealed versus unsealed knitted Dacron® prostheses: a comparison of the acute phase protein response. Ann. Vasc. Surg., 1987, 1: 542 - 547.*

25. *Drury J.K., Aston T.R., Cunningham J.D., Maini R. & Pollock J.G. Experimental and clinical experience with a gelatin impregnated Dacron® prosthesis. Ann. Vasc. Surg., 1987, 5: 542 - 547.*

26. *Harasaki H., Kiraly R.J. & Nose Y., Blood-blood pump surface interaction. In Biocompatible polymers, metals and composites, M. Zycher (ed.), Technomic, Lancaster, 1983. In Sottiurai (1989) q.v.*

27. *Pollock J.G., Drury J.K., Caschieri R.J., et al., New knitted Dacron® prostheses: experimental and clinical results. Revs. Bras. Angiologia e Chirurgia Vascular, 1987. In Sottiurai (1989) q.v.*

28. *Lundsgaard-Hansen P. & Tschirren B. Clinical experience with 12,000 units of modified fluid gelatin. Proc. Joint WHO/IABS Symposium on Standardization of Albumin, Plasma Substitutes and Plasmopheresis, 1981, 48: 251 - 256.*

29. *Reigel M.M., Hollier L.H., Pairolero P.C. & Hallet J.W. Early experience with a new collagen-impregnated aortic graft. Am. Surgeon, 1988, 54: 134 - 136.*

30. *Haimovici H. History of vascular surgery. In Vascular Surgery: Principles and Techniques, H. Haimovici (ed.) Appleton-Century-Crofts, Norwalk, 1984, pp 3 - 18.*

2. THE TWILL WOVEN PROSTHESIS.

2.1. INTRODUCTION:

Vascular prostheses constructed from polyester fibres have proved to be the most reliable arterial substitutes for the replacement and bypass of diseased large and medium arteries. A number of different types containing either different textile constructions or different types of yarns have emerged over the years but the woven construction is preferred for the repair of abdominal aortic aneurysms[1] and for the replacement of the thoracic aorta because of its greater stability and superior ability to control blood loss[2,3]. The woven prosthesis is said, however, to be more difficult to suture and handle and to suffer from inferior healing[4,5] on account of poor attachment of the internal and external capsules to its smooth fabric surface[6].

To overcome these deficiencies, Vascutek Limited, a manufacturer of medical devices in Inchinnan, Scotland, UK, has recently developed a new prototype called the Twill Woven prosthesis intended for use as an arterial substitute. Having a more open structure than the plain weave, the twill construction is expected to give a more flexible prosthesis which will also be easier to suture and handle. Despite assumptions as to the merits of a new product, a notice of compliance must be obtained from a regulatory agency (like the Bureau of Radioprotection and Medical Devices) before it can be put on the market. These regulatory agencies recommend testing of the new prosthesis to establish its merits.

The purpose of this study, therefore, was to evaluate the <u>in-vitro</u> (textile, physical and chemical) and <u>in-vivo</u> characteristics of a new prototype, Twill Woven vascular prosthesis (developed by Vascutek Ltd., Scotland) and to compare these characteristics to those of commercially available woven prostheses that have proved to be successful in the past.

2.2. *IN VITRO INVESTIGATION:*

2.2.1. *Graft selection:*

In addition to the Twill Woven prototype, other woven prostheses manufactured from poly(ethylene terephthalate) polyester were selected as controls. These prostheses are listed in Table 1. Some of these prostheses have been characterized and the information published in the references cited in Table 1.

2.2.2. *Textile properties:*

Testing was done under ambient conditions. In view of the fact that polyester has a moisture absorption level of 0.5%, testing under these conditions would not alter the results of the physical properties obtained.

2.2.2.1. *Surface morphology:*

Scanning electron microscopy was used to observe the surface morphologies of the prostheses. Small samples, mounted on stubs, were exposed to osmium tetroxide vapours and coated with gold-palladium to improve their conduction. They were then examined under a Jeol JSM-35CF scanning electron microscope (Soquelec, Montreal, QC, Canada) at an accelerating voltage of 15 kV. SEM micrographs of the surfaces of the prostheses were taken. This technique provided some information on the type of fabric construction, the type of yarn and the filament cross-section.

2.2.2.2. *Woven fabric count:*

Each specimen, flattened between two glass slides, was examined under an optical macroscope at 12 times magnification using dark field illumination. Five specimens were taken from each sample and the average numbers of warp yarns per centimetre width and weft yarns per centimetre length of the prosthesis were counted.

2.2.2.3. Fabric thickness:

The fabric thickness (in millimetres) for each of ten specimens taken from each prosthesis, was measured on a Custom Scientific Instrument (Whippany, N.J., USA) thickness tester at an applied pressure of 45 g cm^{-2}. The ten measurements were averaged to give the fabric thickness for each sample.

2.2.2.4. Mass per unit area:

A known area of the prosthesis was weighed on a scientific balance with 0.01 mg precision and the weight obtained divided by the area of the specimen was converted to the mass per unit area (in g m^{-2}) of the prosthesis. Five specimens were taken from each prosthesis and the results averaged to give the mass per unit area for each sample.

2.2.2.5. Yarn filament count:

Five warp and five weft yarns were selected randomly from each prosthesis. Each yarn was unravelled under an optical macroscope at 20 times magnification and the number of filaments in the yarn counted. The filament count for each yarn was the mode value of the five measurements.

2.2.2.6. Filament diameter:

The average diameter (in μm) was calculated from measurements taken on twenty specimens at 400 times magnification using an optical microscope with a calibrated eyepiece micrometer.

2.2.2.7. Porosity[7,13]:

The fraction of all the spaces, or voids to the total volume of the material, was calculated using the following equation:

$$P = 100 \left[1 - M/1000h\rho \right]$$

where P is the percentage porosity, M is the mass per unit area of the

prosthetic wall in g m^{-2}, h is the fabric thickness in mm, and ρ is the density of polyethylene terephthalate (1.38 g cm^{-3}).

2.2.2.8. Yarn nominal linear density:

This is a measure of the coarseness of a yarn in units of mass per unit length (decitex). For a filament with a circular cross-section, the following equation gives the filament nominal linear density:

$$\frac{\pi \rho}{100}\left[\frac{d}{2}\right]^2$$

ρ is the relative density of the filament in g cm^{-3}, and d is the filament diameter in μm. For each prosthesis evaluated, the yarn nominal linear density was calculated by multiplying the above equation by n, the number of filaments in the yarn.

2.2.3. Physical properties:

2.2.3.1. Water permeability:

This is defined as the number of millilitres of filtered or distilled water that passes through one square centimetre of a material per minute at a pressure head of 120 mmHg and was determined according to standard procedures[7].

2.2.3.2. Bursting strength:

A Hoffman-Turner probe tester in a compression cell mounted on an Instron Model 1130 tensile tester[7] (Instron Canada Ltd., Laval, QC., Canada) was used to measure the bursting strength of the virgin prostheses. Each specimen was mounted over the 8.1 mm diameter hole using a rubber O-ring of diameter 12.6 mm. A cylindrical probe (6.4 mm diameter) with a hemispherical end was forced through the clamped specimen at a constant rate of 100 mm/min. For each prosthesis, five specimens were tested in order to calculate the average bursting strength in Newtons.

2.2.3.4. Dilation:

A Lasermike (model 183-195, Lasermike Inc., Dayton, Ohio) dilation measurement system was used to measure the dilation of the prostheses. A 10 cm segment of each tubular prosthesis was mounted over a tubular latex membrane and was held between two connectors. One was fixed and supplied the internal air pressure to the graft being tested, while the other one was attached to a low-friction track to which a constant longitudinal tension of 0.25 lb was applied. The outer diameter of the graft was scanned by the laser beam while the air pressure was increased from 0 to 340 mmHg, and the acquired data were analysed by computer to determine the mean dilation and standard deviation for each pressure.

2.2.3.5. Suture retention strength:

Measurements of the force required to pull a suture out of the prostheses were made on an Instron Model 1130 tensile tester (Instron Canada Ltd., Laval, QC., Canada) with a cross-head speed of 100 mm min^{-1}*. Specimens cut with scissors to form squares (15 mm x 15 mm) with one corner bevelled at 45° were tested. Tests were conducted at 45°, 90° (perpendicular) and 0° (parallel) to the longitudinal axis of the prosthesis. Each specimen was held by a specially designed pair of clamps provided with a groove to allow a 4-0 stainless steel suture to pass through the prosthetic wall exactly 2 mm from the cut edge. The force required to pull the suture from the graft was measured in newtons and the average of five measurements from each prosthesis was taken as the average suture retention strength.*

2.2.4. <u>Chemical properties:</u>

2.2.4.1. Infrared spectroscopy (FTIR-ATR):

Spectra were obtained on a Bomem Model DA3-02 FTIR spectrophotometer (manufactured by Bomem Inc., Hartmann and Braun, Québec, Canada) with a Wilks ATR attachment. Specimens (5 cm x 2 cm) were cut and

clamped within a KRS-5 crystal assembly with the help of screws. The crystal was mounted on an interface of 45° in the ATR accessory. The reference beam was attenuated and spectra were recorded between 700 and 4000 cm^{-1}. A total of 200 scans was coadded for each specimen.

2.2.4.2. Electron spectroscopy for chemical analysis (ESCA):

Spectra were obtained on a Lab MK2 ESCA machine (manufactured by Vg Scientific) featuring a MgKα beam. Survey scans to determine the levels of contaminants, as well as high resolution spectra of the carbon 1s and oxygen 1s peaks were obtained. Each peak was resolved into its components (i.e C-C, C-O and O-C=O for carbon; C-O and O-C=O for oxygen).

2.2.4.3. Differential scanning calorimetry (DSC):

Ten to twenty milligrams of each specimen were loaded into an aluminium pan, sealed and then heated (from 30° to 300 °C) in an atmosphere of nitrogen with a programmed heating rate of 20°C min^{-1} in a DSC 7 thermal analyser (Perkin Elmer Corporation, Montreal, Canada) calibrated using a known weight of indium. Glass transition (Tg), melting temperature (Tm), heat of fusion (▲H) and crystallinity index were determined for each sample. A total of four specimens was taken from each sample.

2.2.4.4. Level of extractables[14]:

For each prosthesis, five 5 g samples were subjected to a series of multiple quantitative extractions with different solvents cycling in a Soxhlet extraction apparatus. The sequence of solvents in increasing order of polarity was hexane, 1,1,1-trichloroethane, methanol, water and 0.1N HCl. Gravimetric determination of the mass of each extract following evaporation to dryness of the respective solvent was done and the levels of extractable material were expressed as a percentage of the mass of the original sample.

2.3. *IN VIVO* INVESTIGATION:

2.3.1. Animal selection and hematological tests:

Adult mongrel dogs, preferably female, weighing between 16 and 24 kilograms, were selected according to the Canadian Council on Animal Care regulations. In addition to routine hematological tests (i.e. hemoglobin, hematocrit, platelet count, WBC and RBC), blood samples were characterized by platelet aggregation analysis and thromboelastography.

2.3.2. Surgery:

The protocol for a thoraco-abdominal bypass, originally described by McCune and Blades[15] was employed for the evaluation of the new grafts. A series of implantations were performed for prescheduled periods of 4 hours, 1 and 2 days, 1 and 2 weeks, 1, 3 and 6 months. Prior to surgery, the dogs were fasted for 24 hours. They were then anesthesized with 32 mg kg^{-1} of intravenous sodium pentobarbital (Somnotol^R, MTC Pharmaceutical Ltd., Missisauga, Canada), intubated and mechanically ventilated. In addition, 20 mg kg^{-1} of Ketamine^R (Rogar STB Inc., Montreal, Québed, Canada) was administered to maintain anesthesia as required. Intravenous infusions of Ringer's lactate were injected to compensate for dehydration during surgery. The abdomen was shaved and the skin was prepared with Hibitane^R chlorhexidine gluconate (Ayerst, Montreal, Québec, Canada). The thoracic aorta was isolated by means of a left thoracotomy through the 8th intercostal space. The abdominal aorta was mobilized from the renal arteries to the aortic trifurcation through a midline lower abdominal incision. The Twill Woven grafts were preclotted according to the protocol described by Yates et al[16]. All the implants were 8 mm in diameter and 30 cm long. The animals were given 0.5 mg kg^{-1} intravenous heparin (Allen and Hanburys, Glaxo Canada Ltd., Toronto, Ontario, Canada) at least 5 minutes before vascular clamping. The distal anastomosis was performed in an end-to-side manner between the prosthesis and the infrarenal aorta. The graft was then tunnelled in the retroperitoneal and retropleural space. The

thoracic aorta was clamped, sectioned after distal ligation and the proximal end-to-end anastomosis was completed. All the anastomoses were performed with continuous 5/0 polypropylene monofilament suture (Prolene^{R}, Ethicon Sutures Ltd., Peterborough, Ontario, Canada). The rate of blood flow in the graft and the distal abdominal aorta ranged from 1500 and 2000 ml min^{-1} and between 150 and 200 ml min^{-1} respectively, ensuring adequate perfusion of the kidneys throughout the procedure. The abdomen and thorax were closed in layers using 1/0 and 2/0 Prolene^{R} sutures. The animals were returned to their cages and fed an unrestricted standard diet. All animals received intramuscularly at the time of anesthesia 3 ml of Penlong R XL antibiotic (Rogar STB Inc., Montreal, Québec, Canada).

2.3.3. Angiography:

Angiography was performed prior to harvest on grafts for 3 and 6 months using Conray^{R} (Mallinckrodt Canada Inc. Montreal, Québec, Canada) as the contrast medium.

2.3.4. Graft Harvest:

The dogs were returned to the operating room and anesthetized with 32 mg kg^{-1} of sodium pentobarbital intravenously. Blood samples were taken for hematological analyses. An additional 20 ml of blood in sodium citrate was taken for radiolabelling of platelets (see below). Before sacrifice, radiolabelled platelets and fibrinogen were injected in the right femoral vein and allowed to circulate for 30 minutes. Thereafter, heparin (0.5 mg kg^{-1}) was administered intravenously in order to minimize the post-mortem thrombotic deposits over the graft surface. The dog was then exsanguinated via the right fermoral artery. The grafts were removed by a thoraco-phrenolaparatomy, opened longitudinally, carefully rinsed and photographed with a Tessovar microphotography optical system (Carl Zeiss, Oberkochen, Germany) to assess the macroscopic findings. Specimens in the proximal, medial and distal regions were cut for determination of platelet and

fibrin uptake, prostaglandin secretion, and pathological investigation. A segment of adjoining native aorta was also taken as a control for the thrombogenic and prostaglandin secretion studies.

2.3.5. Indium-111 platelet and Iodine-125 fibrinogen uptake studies:

Platelet and fibrin deposition over the graft surface were determined by means of an isotopic technique using indium-111 labelled platelets and Iodine-125 labelled fibrinogen. For platelet labelling, 20 ml of autologous blood in sodium citrate was collected and centrifuged at 1000 RPM for 8 minutes. Platelet Rich Plasma (PRP) was then incubated with 100 μCi of indium-111 oxinate (Amersham, Aylesbury, Bucks, UK) for 15 minutes at room temperature. Two aliquots (0.05 ml) of this labelled suspension were preserved as standards for total radioactive counts. The labelled platelets were then centrifuged at 2500 RPM for 10 minutes. The platelet pellet was resuspended in 2.5 ml of saline, and 2 aliquots (0.05 ml) of the supernatant were preserved as a second standard for radioactive count remaining in the suspension. Two aliquots (0.05 ml) of labelled platelets were also counted. A commercial solution of labelled Iodine-125 fibrinogen (Amercham Canada, Oakville, Ontario, Canada) was dissolved in 1.1 ml of distilled water. Two aliquots (0.01 ml) were preserved as standard. Thirty minutes before sacrifice, the labelled platelets and 10 μCi of labelled fibrinogen were both injected in the right fermoral vein. Platelet and fibrin uptake over 2 cm segments of the proximal, medial and distal regions of each prosthesis as well as the thoracic aorta was determined with a two-channel gamma scintillation counter LKB Rack Gamma (Fisher, Montreal, Québec, Canada) adjusted to 20-85 Kev for Iodine-125 and 200-300 Kev for Indium-111. The amount of uptake per centimetre was expressed as a percentage of the total amount of labelled platelet and fibrinogen injected into the animal. The amount of uptake on the native thoracic aorta control segment served as a baseline.

2.3.6. Prostacyclin (PGI_2) and thromboxane A_2 (TXA_2) Synthesis:

The stable hydrolytic products of prostacyclin (PGI_2), 6-keto-PGF_1, and thromboxane A_2, were measured by radioimmunoassay. Fresh 1 cm^2 segments of prostheses were removed from the proximal, medial and distal regions and analyzed immediately for PGI_2 and TXA_2 quantitation. Segments were incubated with 2 ml of Tris buffer (0.05M Tris-HCl, pH 7.5) for 30 minutes at 37 °C. Aliquots of the buffer were either quick-frozen or immediately tested using a 6-keto-PGF_1 (^3H) RIA kit and a thromboxane B_2 (^3H) RIA kit (New England Nuclear, Boston, MA, USA). Segments of each region of grafts were tested in duplicate and the results for statistical analysis expressed as the mean PGI_2/TXA_2 ratio of the 3 tested regions.

2.3.7. Histological and scanning electron microscopy studies:

Pathological analysis was conducted on the proximal and distal anastomotic regions as well as the medial region of each graft. Each specimen was divided into two. The first half was fixed in a 2% isotonic buffered glutaraldehyde solution, rinsed in distilled water and postfixed in osmium tetroxide. The drying process consisted of immersion in a series of aqueous ethanol solutions followed by critical point drying using liquid CO_2 as the transfer medium. The dried specimen was then coated with gold-palladium and examined using a Jeol JSM 35 CF scanning electron microscope (Soquelec, Montreal, Québec, Canada) at an accelerating voltage of 15kV. The second portion was fixed in a 10% solution of formalin and 5 µm sections were cut and stained as follows: Hematoxylin-Eosin, Weigert, Masson trichrome, Brown and Brenn.

*2.4. **EXPLANTED MATERIALS:***

2.4.1. Cleaning protocol:

The explanted material was boiled in 5% sodium bicarbonate solution for 5 minutes, rinsed in distilled water and then immersed in 5% sodium hypochlorite solution at 25 °C for 2 hours. This was followed by several

rinses in distilled water. A virgin prosthesis was also cleaned by the same procedure to serve as the control.

The cleaned samples were then subjected to the following: woven fabric count, filament diameter and bursting strength measurements, surface analysis using FTIR-ATR techniques and thermal analysis using differential scanning calorimetry. These tests have already been described in section 2.

2.5. RESULTS:

2.5.1. In vitro evaluation:

2.5.1.1. Textile properties:

The textile characteristics for all of the prostheses evaluated are listed in Table 2. The Twill Woven prosthesis incorporates, on its external surface, a modified plain weave construction featuring two sets of repeating warp floats in every six warp ends. The internal surface, on the other hand, shows a 1/1 plain weave construction. The fabric is constructed in such a way that the warp floats cover the adjacent yarns having a 1/1 interlacement so that when one unravels a repeat that looks like four yarns, one actually observes six yarns in the repeat. This gives an impression of 42 rather than the actual 64 ends per centimetre. Figures 1-7 are point diagrams showing the type of woven construction of the different prosthesis analysed. In addition, they include cross-sectional diagrams showing the sequence of yarn interlacements for the first set of 12 warp yarns in each prosthesis. SEM photographs of the internal and external surfaces of the prostheses are shown in figure 8.

The long warp floats are clearly visible on the external surface of the Twill Woven prosthesis. Floats are also found on the surfaces of the Meadox Woven Double Velour, the Impra, the Chinese Filamentous and the Velex prostheses. The difference between the structures of these prostheses lies in the lengths of the floats, their sequence of yarn interlacements and the surfaces on which the floats are present. The

Meadox Woven Double Velour, for instance, incorporates a 6/4 satin weave so that warp floats are found on both its internal and external surfaces. The lengths of the floats on both surfaces are longer than those found on the Twill Woven prosthesis.

In addition to the long floats on the external surface of the Twill Woven prosthesis, the graft has other unique features. One of these is its light weight. The low fabric thickness (0.33 mm) and the mass per unit area of 172 g m^{-2} contribute to this property. The prosthesis is also flexible, a property which may be attributed to both its weave type and yarn structure (Table 3). The Twill Woven graft was produced from flat and thin multifilament yarns with nominal linear density of 102 decitex. These are fine yarns with very little or no twist, hence the flexibility of the prosthesis. The filament diameter of 13.2 - 14.2 µm is similar to those of the other grafts which also incorporate long floats on their surfaces. Only the Chinese Filamentous prosthesis had thicker filaments with an average diameter of 20.9 µm (Table 3).

The structure of the Twill Woven prosthesis described above is expected to be associated with a prosthesis having a higher porosity than the normal 1/1 taffetta, plain weave structures. This was not, however, reflected in the calculated porosity value for the Twill Woven prosthesis. The value of 62% obtained for the Twill Woven prosthesis was somewhat higher than the average value for the 1/1 plain weaves but was similar to the porosity of the Impra Low Porosity graft with its mixed satin and plain weave structures (Table 2).

2.5.1.2. Physical properties:

The physical properties of the woven prostheses are listed in Table 4 and represented diagramatically in Figure 9. The bursting strength of 280 Newtons obtained for the Twill Woven prosthesis was similar to that of the Meadox Woven Double Velour but was higher than the values obtained for the Impra High Porosity and the Chinese Filamentous prostheses. The

water permeability (80 ml min^{-1} cm^{-2}), on the other hand, was amongst the lowest value obtained and the dilation at 120 mmHg was low (0.4%), lower than the values obtained for the Intervascular Ochsner 500 (1.2%), the Impra High Porosity (1.9%) and the Meadox Woven Double Velour (2.0%). The suture retention strength measured at 90° to the longitudinal axis of the Twill Woven prosthesis was higher than the values obtained at 0 or 45°. This trend was observed with most of the other prostheses evaluated. However, the Meadox Woven Double Velour, the DeBakey Extra Low Porosity, the Woven Vascutek, the Indian and the Velex had higher suture retention strengths in the longitudinal axes of the prostheses i.e at 0°.

2.5.1.3. Chemical properties:

2.5.1.3.1. Electron spectroscopy for chemical analysis (ESCA):

The results of the survey scans showed that, in general, the level of contaminants was higher on the external surface than on the internal surface for the prostheses evaluated (Table 5). The Twill Woven prosthesis was relatively clean compared to some of the other prostheses evaluated. Figure 10 shows the ESCA survey scan obtained for the Twill Woven prosthesis and Figure 11 shows the C1s and O1s high resolution spectra. The C1s and O1s peaks for each prosthesis were resolved into components and contrary to the expected ratio of 6:2:2 for the C1s components and 1:1 for the O1s components of pure poly(ethylene terephthalate), variations were found to occur in the ratios obtained for the C1s and O1s components from one prosthesis to the other (Table 6). These variations indicate differences in manufacturing and/or handling techniques.

2.5.1.3.2. Differential scanning calorimetry:

Thermal analyses on each virgin prosthesis allowed measurements of the glass transition temperature (Tg), the peak melting temperature (Tm) and the heat of fusion (▲H) from which the crystallinity index was calculated. The results are presented in Table 7 and Figure 12 shows

representative DSC thermograms for the Twill Woven prosthesis. The glass transition temperature for all of the prostheses analyzed was observed between 70 and 80°C. The Twill Woven prosthesis had the lowest Tg (71.6°C), closest to the reported[17] value for amorphous poly(ethylene terephthalate) and the Woven Braun Melsungen had the highest value. The peak melting temperature for the Twill Woven prosthesis was observed at 261 °C and with the exception of the Intervascular Ochsner 500 which showed a melting peak at 254 °C, all of the other prostheses had melting peaks between 256 and 261 °C. These values are in agreement with literature[17, 18] values of Tg ang Tm for poly(ethylene terephthalate).

The measured heats of fusion for the prostheses evaluated ranged from 55.27 to 60.44 J/g. These were used to calculate crystallinity indices for the samples based on the heat of fusion for 100% crystalline polyester (140 J/g)[19]. The Twill Woven prosthesis had a crystallinity index of 0.40 while the other prostheses had crystallinity index values ranging from 0.39 - 0.43.

2.5.1.3.3. FTIR-ATR:

Figure 13a shows typical FTIR-ATR spectra obtained for the virgin polyester prostheses. For the Twill Woven prosthesis, the ester carbonyl (C=O) stretch was observed around 1712 cm^{-1} while the ester C-O stretch was observed around 1237 and 1091 cm^{-1} (Figure 13b). In addition to these strong bands, peaks were also observed at 1577, 1504, 1473, 1408, 1341, 1016, 971, 896, 871, 845 and 789 cm^{-1}. The observed peaks and their assignments are listed in Table 8. These peaks were present in the spectra of all the other prostheses evaluated. It was also observed that the Protegraft Braun Low Porosity, the DeBakey Extra Low Porosity and the Soft Woven DeBakey prostheses showed a more pronounced shoulder around 1259 cm^{-1} (O-C ester stretch) compared to the other prostheses. This was the major difference observed in the spectra of the different prostheses. Figure 13c shows the spectrum of the DeBakey Extra Low Porosity overlaid on that of

the Twill Woven prosthesis to highlight this difference.

2.5.1.3.4. Level of extractables:

The total level of extractables (1.5) for the Twill Woven prosthesis is higher than that measured for the other prostheses (Table 9). The highest level was obtained with methanol (0.7%) suggesting the presence of unfixed cellulose reactants, organic salts and sulphonated organics. The presence of oils, waxes, softeners and silicones may be indicated by the level of extractables found in hexane (0.5%). The silicon level of 0.4% found on the surface of the Twill Woven prosthesis from ESCA analysis agrees with this observation. Extraction with water followed by 0.1N HCl yielded very little amounts of fixed cellulose reactants, branched starches, inorganic salts, urea, linear starches, and polyvinyl alcohol. Finally there were no unfixed polymers, polyester resins, acrylics, polyurethanes and polyvinyl acetate as indicated by the 0% level of extractables found in 1,1,1-trichloroethane.

2.5.2. <u>In vivo investigation:</u>

2.5.2.1. Implantation, follow up and hematological analyses:

All implantations were successful, thus 8 dogs were required to complete the implantation schedule. The Twill Woven graft exhibited excellent handling characteristics during operation and was very easy to suture. The time required to complete the two anastomoses was 25.5 ± 2.2 minutes on the average.

Angiographies were performed at 3 and 6 months prior to the sacrifice to assess the patency and morphology of the graft. The Twill Woven graft explanted at 3 months was slightly stenosed in the retroperitoneal tunnel and bent near the proximal and distal anastomoses. The graft explanted at 6 months was patent and straight. The hematological profile of each dog was taken before the operation and at sacrifice to detect any changes in hematological parameters. In general, all the dogs

experienced a decrease in platelet counts at the time of sacrifice which correlated with an increase in the time of coagulation (Hemochron). On the other hand, an increase in leukocyte count was observed at 24 and 48 hours after implantation. This corresponds to an acute response to a foreign material. After one week, the leukocyte counts were similar to those observed before the operation. However, the implantation of the preclotted Twill Woven grafts did not induce any increase in the thrombogenic index for all periods of implantation.

2.5.2.2. Macroscopic observations:

The macroscopic and healing characteristics of the preclotted Twill Woven grafts are presented in Table 10. A thin thrombotic matrix mainly located in the fabric crimps was present at 4 and 24 hours after implantation. The grafts became cleaner at 48 hours as partial filling of the crimps with thrombotic material was observed. The luminal surface was generally smooth after 1 week with few filled crimps in the mid portion of the grafts. The encapsulation of the grafts by granulomatous tissue was completed at one month. Slight bends were noted with the Twill Woven grafts explanted at 1 and 3 months.

2.5.2.3. Histological and SEM studies:

The luminal surface of the preclotted Twill Woven grafts explanted at 4, 24, 48 hours and 1 week respectively was covered by a thin thrombotic matrix associated with a moderate inflammatory reaction with polymorphonuclear cells (PMNs) and lymphocytes (Figure 14). The thrombotic material consisting of a fibrin network entrapping blood cells was in general located in the crimps of the grafts (Figure 15). At 2 weeks, the development of a collagenous internal capsule was underway at both anastomoses with the presence of endothelial cells (Figure 16). At 1 month, collagenous internal capsule extended from both anastomoses and was endothelialized. The mid-portion of the graft showed a luminal surface in

a state of reorganization (collagen positive). The inflammatory reaction was moderate and chronic. Both preclotted Twill Woven grafts explanted at 3 and 6 months exhibited similar healing characteristics mainly a thin collagenous internal capsule covering the entire graft which was smooth, regular and filling the crimps (Figure 17). The cellularity of the internal capsule was evident under light microscopy and an endothelial lining was observed by SEM covering the luminal surface (Figure 18). The inflammatory reaction was discrete and limited to the polyester yarns.

2.5.2.4. Fibrin and platelet uptake:

The fibrin and platelet uptake over the luminal surface of the preclotted Twill Woven grafts is shown in Table 11 and calculated as a percentage of labelled fibrin and platelets in CPM present on the graft surface after 30 minutes by the total quantity of labelled fibrin and platelets injected. Fibrin accumulation on the graft surface was of the order of 10^{-2} whereas the percentage of platelets was in the range of 0.2 - 0.6%. Fibrin and platelet accumulations were more important over the proximal and medial regions than distally. These results show the low thrombogenicity of the preclotted Twill Woven grafts.

2.5.2.5. Prostaglandin secretion:

The ratio of PGI_2/TXA_2 was used to evaluate the luminal surface function of the preclotted Twill Woven grafts. It is expressed as the mean ratio PGI_2/TXA_2 determined on the proximal, medial and distal regions for each period of implantation. The pattern of PGI_2/TXA_2 secretion showed a ratio below 1.0 for the grafts explanted at 4, 24, 48 hours and 1 week. The ratio reached 1.0 at 2 weeks with the simultaneous endothelialization of the grafts. Thereafter, the mean ratio for the preclotted Twill Woven at 6 months reached 6.7 ± 5.6. The mean ratio secreted by the control thoracic aorta was 52.4 ± 37.8; $\mu = 8$.

2.5.3. Cleaned explanted grafts:

2.5.3.1. Textile properties:

The data obtained for the textile properties of the cleaned, explanted Twill Woven grafts are presented in Table 12. The filament diameter showed very little or no change with implantation time, neither did the fabric count.

2.5.3.2. Physical properties:

With the limited amount of explanted materials available, only bursting strength tests could be performed on the explanted samples. For some implantation times, the explanted samples were too small even for one bursting strength measurement to be taken. The results are presented in Table 13. The graft explanted after four weeks had an average bursting strength of 340 ± 7.1 N. This average was obtained from only two measurements and is much higher than the bursting strength of the virgin (280 N) or the cleaned control (325 N). The other values are also higher than those of the two controls but with the limited amount of data available, no definite conclusion about these observations could be made.

2.5.3.3. Chemical properties:

Typical FTIR-ATR spectra obtained for the cleaned, explanted grafts are presented in Figure 19. In addition to the peaks observed in the spectra of the virgin Twill Woven prosthesis, infrared features were also observed between 2800 and 3000 cm^{-1} and a shoulder on the high frequency side of the infrared absorption due to the carbonyl ester stretching mode of PET polyester was evident, an indication that molecules were absorbed/adsorbed onto the surface of the prosthesis. Moreover, the intensity of these additional peaks became more pronounced as the length of implantation increased, indicating an increase in the concentration of the adsorbed molecules. In order to highlight these spectral modificaftions and to determine the type of molecule adsorbed on the

surface of the Twill Woven prosthesis, the infrared spectrum of the virgin graft (Figure 20b) was subtracted from that of the explanted material (Figure 20a) using the band at 871 cm^{-1} as an internal intensity standard. The result of this mathematical operation, presented in Figure 20c, shows typical absorption bands of lipidic molecules. A comparison of the spectrum of Figure 20c with that of a phospholipid (dimyristoyl-phosphatidic acid, DMPA) presented in Figure 20d shows a high concordance between both spectra. The bands observed at 2920 and 2851 cm^{-1} (2925 and 2853 cm^{-1} for molecules adsorbed on the prosthesis) were assigned to the acyl chain methylene antisymmetric and symmetric stretching modes respectively. Weaker bands due to the asymmetric and symmetric stretching modes of the terminal methyl groups of the lipid acyl chains were also present at 2958 and 2872 cm^{-1} respectively. These bands were not well defined in the spectrum of Figure 20c and appeared only as shoulders at 2953 and 2873 cm^{-1} since the signal to noise ratio in the CH stretching mode region was not sufficiently high. In addition, peaks characteristic of the ester carbonyl stretching and CH_2 deformation modes were also detected at 1739 and 1469 cm^{-1} (1747 and 1464 cm^{-1} for molecules adsorbed on the explanted prosthesis). Other infrared features observed between 1400 and 750 cm^{-1} were mainly due to vibrations of the lipid head group. Since the lipidic molecules adsorbed on the surface of the Twill Woven prosthesis probably consist of a mixture of several molecules with different head groups, correlation between these two infrared spectra could not be done in this region.

2.5.3.4. DSC Data for explanted materials:

For the explanted materials, the DSC data are presented in Table 14. The crystallinity index was constant at 0.40 showing no change in the crystallinity of the prosthesis with implantation. This observation is in agreement with the previously reported stability of polyester <u>in vivo</u>. In addition, the very little variation in average peak temperatures for the

explanted samples as a function of implantation time agreed with the observed constancy of the crystallinity index.

2.6. DISCUSSION:

Tightly woven taffetta type prostheses are known to have great strength and a superior ability to control blood loss at implantation. They are, however, difficult to suture and handle and suffer from inferior healing on account of poor attachment of the internal and external capsules to the smooth fabric surface. In order to improve on these limitations, several approaches have been adopted, the most recent being the introduction of the twill construction in the manufacture of woven prostheses. A twill weave, by definition[20], is one in which each warp or weft yarn floats across two or more filling or warp yarns with a progression of interlacings by one to the right or left to form a distinct diagonal line or wale.

Some characteristics associated with such a structure which may be relevant to the performance properties and healing characteristics of a vascular graft include: the presence of longer floats (compared to the taffetta type structure) with greater exposure of filaments on the surface of the fabric; fewer interlacements due to the long floats resulting in reduced stiffness, increased bending, shearing and buckling characteristics; and greater yarn mobility due to the fewer number of interlacements.

The "Twill Weave" structure as employed by graft manufacturers, actually incorporates a modified plain weave with two sets of repeating warp floats in every six warp ends (Figure 1). Though different from the definition of a twill weave given above, it shares the same characteristics which are relevant to the performance properties and healing characteristics of a graft. The <u>in vivo</u> and <u>in vitro</u> characteristics of the Twill Woven prototype observed in this study will be discussed with reference to the these characteristics.

The performance characteristics of the Twill Woven prototype were similar to those of taffetta type prostheses. The incorporation of long warp floats resulted in a reduction of the fabric tightness (because fewer warp and weft yarns formed the ground structure) without affecting the water permeability. Of all the prostheses evaluated, the Twill Woven had the lowest water permeability. This property alerts the surgeon to the need for preclotting the prosthesis with the patients blood prior to implantation. The in vivo animal study showed that preclotting was easy and there was no blood loss at implantation. In addition to maintaining a low water permeability, the reduction in fabric tightness compromised neither the bursting strength nor the dilation and the suture retention strength of the Twill Woven prototype.

The ease of handling and suturability of the Twill Woven prosthesis can be accounted for by the presence of long floats. The fewer interlacings per unit area gave rise to reduced stiffness, increased bending, shearing and buckling characteristics compared to taffetta type structures. In addition, the fewer number of interlacements per unit area is expected to result in greater yarn mobility thus leading to improved healing over the smooth walled plain woven structure. The improvement in healing capacity would be due to the enhancement of tissue infiltration which would allow for capillary regeneration and adequate blood supply to the surrounding capsules. The in vivo animal studies indicated satisfactory healing in accordance with the usual sequence observed in polyester prostheses.

One other favorable characteristic which may be attributed to the fabric construction and the presence of fewer interlacements per unit area is a reduction of the problem of detachment of thrombotic matrix as well as the probability of graft stenosis as evidenced in prostheses with thick pile surfaces. However, fraying at the cut edges is possible because of the presence of long floats in the fabric. The suture retention strength was higher in the longitudinal direction which implies that end to end

anastomoses might be better for this particular prosthesis.

*2.7. **CONCLUSION:***

The results of this study have shown that the Twill Woven prosthesis heals satisfactorily in accordance with the healing sequence observed in other polyester prostheses. It also has excellent suturing and handling characteristics and it compares favorably with the control prostheses currently in use. However, further studies are recommended to determine the effect of longer implantation times on the stability of the prosthesis. In addition, implantation in other animal models is recommended to confirm the stability or non stability of the Twill Woven prostheses <u>in vivo</u> prior to implantation in human beings.

2.8. REFERENCES:

1. *Eastcott H.H.G. An appraisal of the use and function of vascular grafts in England. In Vascular Grafts, (P.N. Sawyer & M.J. Kaplitt (eds.), Appleton Century Crofts, New York, USA, 1978, pp 220-225.*

2. *Bloodwell R.D., Hallman G.L., Beall A.C., Cooley D.A. & DeBakey M.E. Aneurysms of the descending thoracic aorta: surgical consideration. Surg. Clinics Ass. N. Am., 1966, 46: 901-911.*

3. *Pan C. & Rao T.J. Experimental research and clinical results of the local-made polyester arterial prosthesis. J. Jap. Soc. Chest Surg. 1982, 30: 43-50.*

4. *Callow A.D. Current status of vascular grafts. Surg. Clinics Ass. N. Am., 1982, 62: 501-513.*

5. *Edwards W.S. Arterial grafts: past, present and future. Arch. Surg., 1978, 113: 1225-1233.*

6. *DeBakey M.E., Jordan G.I., Beall A.C., O'Neal R.M., Abbott J.P. & Halpert B. Basic biologic reactions to vascular grafts and prostheses. Surg. Clinics Ass. N. Am., 1965, 45: 477-497.*

7. *National standard for vascular graft prostheses, ANSI AAMI VP20 1986. Association for the Advancement of Medical Instrumentation, Arlington, VA, USA.*

8. *Guidoin R., King M., Therrien M., Douville Y., Debille E., Boyer D., Simoneau S., Tremblay L. Woven velour polyester arterial grafts with polypropylene wrap: a cosmetic change or improved design? In High Performance Biomaterials: A Comprehensive Guide to Medical and Pharmaceutical Applications. M.Szycher (ed). 1991, pp 449-474.*

9. King M., Blais P., Guidoin R., Prowse E., Marois M., Gosselin C., & Noel H.P. Polyethylene Terephthalate (Dacron®) vascular prostheses - material and fabric construction aspects. In CRC Handbook: Biocompatibility of Clinical Implant Materials II. D.F. Williams (ed). CRC Press, Boca Raton, Florida, 1981, pp 177-207.

10. Paynter R.W., King M., Guidoin R.G., Rao T. The surface composition of commercial polyester arterial prostheses - an XPS study. The Intl. J. Artif. Organs, 1989, 21: 189-194.

11. Rao T., Pan C., Guidoin R., Marceau D., Roy P., King M., Badour B., Rui J., Cheng H., Li C., Qian X., & Lin C. Soft filamentous woven polyester arterial prosthesis from China. Biomaterials, 1991, 12: 335-343.

12. Guidoin R., King M., Gosselin C., Blais P., Gunasekera K., Marois M., & Cardou A. Les prothéses artérielles en polyester. Rev. Eur. Tech. Biomed., 1982, 4: 13-25.

13. Finishes in textiles: identification. Test Method 94-1985, Technical Manual, American Association of Textile Chemists and Colorists, Research Triangle Park, NC, USA. 1987.

14. Guidoin R., King M.W., Marceau D., Cardou A., De la Faye D., Legendre J.M., & Blais P. Textile arterial prosthesis: is water permeability equivalent to porosity. J. Biomed. Mater. Res. 1987, 21: 65-87

15. McCune W.S. & Blades W. The viability of long blood vessel grafts. Ann. Surg., 1954, 134: 769-781.

16. Yates S.G., Burros A.A.B., Berger K., Fernandez L.G., Wood S.J., Rittenhouse E.A., Cavis C.C., Mansfield P.B. & Sauvage L.R. The preclotting of porous arterial prostheses. Am. J. Surg., 1978, 188: 611-622.

17. Elenga R., Seguela R., & Rietsch F. Thermal and mechanical behaviour of crystalline poly(ethylene terephthalate): effects of high temperature annealing and tensile drawing. Polymer, 1991, 32: 1975-1982.

18. Lawton E.L., & Ringwald E.L. Physical constants of poly(oxyethylene-oxyterephthaloyl) (poly(ethylene terephthalate) in Polymer Handbook. J. Brandrup & E.H. Immergut (eds.), 1989, pp V102-V106.

19. Mehta A., Gaur U., & Wunderlich B. Equilibrium melting parameters of poly(ethylene terephthalate). J. Polymer Sci.: Polymer Phys. Ed. 1978, 16: 289-296.

20. Hollen N. & Saddler J. Textiles, Macmillan Co., New York, New York, 1968, pp 144.

2.9. TABLES:

TABLE 1: WOVEN POLYESTER PROSTHESES SELECTED AS CONTROLS IN THE COMPARATIVE EVALUATION OF THE TWILL WOVEN PROSTHESIS.

Prostheses	*Manufacturer*
Soft Woven DeBakey[8,10,11]	*C.R. Bard.*
DeBakey Extra Low Porosity[12]	*C.R. Bard.*
Woven Vascutek[10]	*Vascutek Ltd.*
Meadox Woven Double Velour[8,11]	*Meadox Medicals.*
Meadox Cooley Verisoft[8-12]	*Meadox Medicals.*
Intervascular Ochsner 200[8]	*Intervascular Ltd.*
Intervascular Ochsner 500[8]	*Intervascular Ltd.*
Impra Low Porosity[8]	*Impra Inc.*
Impra High Porosity[8]	*Impra Inc.*
Chinese Filamentous High Porosity[10,11]	*Suzhou, Jiangsu.*
Woven Chinese Low Porosity[10,11]	*Suzhou, Jiangsu.*
Braun Protegraft Low Porosity	*B. Braun Melsungen.*
Indian[10]	*Sree Chita Tirunal Institute.*
Velex	*C.R. Bard.*

TABLE 2: TEXTILE PROPERTIES FOR WOVEN, VIRGIN, POLY(ETHYLENE TEREPHTHALATE) PROSTHESES

Prostheses	Type	Ends cm^{-1}	Picks cm^{-1}	Thickness (mm)	Mass/Unit Area (g/m^2)	Porosity (%)
Twill Woven	1/1 plain + 3/1/1/1 float	42p 22f	48	0.33	172	62.2
Soft Woven DeBakey	1/1 plain weave	52	32	0.26	154	57.1
DeBakey Extra Low Porosity	1/1 plain weave	55	40	0.36	192	61.0
Vascutek Woven	1/1 plain weave	56	30	0.29	175	56.3
Woven Double Velour	6/4 satin + 1/1 plain weave	36s 36p	38	0.32	184	58.3
Meadox Cooley Verisoft	1/1 plain weave	58	35	0.27	152	59.2
Ochsner 200	1/1 plain + leno weave	42p 14l	21	0.32	185	58.6
Ochsner 500	1/1 plain + leno weave	42p 14l	21	0.26	142	60.6
Impra Low Porosity	3/1 satin + 1/1 plain weave	36s 36p	29	0.51	273	61.2
Impra High Porosity	3/1 satin + 1/1 plain weave	32s 32p	25	0.43	186	68.7
Chinese High Porosity	4/1 satin weave	45	62	0.39	117	78.3
Chinese Low Porosity	1/1 plain weave	49	27	0.28	200	48.3
Woven Braun	1/1 plain weave	56	34	0.47	367	43.4
Indian	1/1 plain weave	38	39	0.37	298	41.6
Velex	1/5 twill + 1/1 plain weave	70	28p 28f	0.31	336	21.5

TABLE 3: YARN PROPERTIES FOR VIRGIN PET PROSTHESES

Prostheses	Yarn type linear	Yarn nominal density (decitex)	Approximate filament count	Filament diameter (μm)	Delusterant level
Twill Woven	flat mf	102	54 warp p	13.2±1.3	semi dull
		102	54 warp f	13.2±1.3	semi dull
		118	54 weft	14.2±1.7	semi dull
Soft Woven DeBakey	textured mf	170 warp	108 warp	11.6±1.1	bright
		170 weft	108 weft	12.5±1.2	bright
Debakey EL Porosity	textured mf	170 warp	108 warp	12.1	semi dull
		170 weft	108 weft	12.1	semi dull
Woven Vascutek	textured mf	180 warp	100 warp	12.8±1.2	semi dull
		90 weft	50 weft	13.2±0.5	semi dull
Meadox Woven Double Velour	textured s	120 warp s	54 satin	14.4±0.4	semi dull
	flat warp p	105 " p	54 plain	13.5±0.7	semi dull
	flat weft + textured mf	105 + 120	54 + 54	13.5±0.8 14.4±0.4	semi dull
Cooley Verisoft	flat mf	190 warp	108 warp	13.0±0.5	semi dull
	flat mf	100 weft	54 weft	13.3±0.5	semi dull
Ochsner 200	textured mf	285 warp p	102 warp p	16.4±1.4	semi dull
		95 warp l	34 warp l	16.5±2.3	semi dull
		190 weft	68 weft	17.2±1.9	semi dull
Ochsner 500	textured mf	190 warp p	68 warp p	16.8±1.9	semi dull
		95 warp l	34 warp l	16.3±1.5	semi dull
		190 weft	68 weft	15.8±0.6	semi dull
Impra Low Porosity	textured mf	210 warp s	108 warp s	13.9±0.6	semi dull
		210 warp p	108 warp p	13.2±0.6	semi dull
		315 weft	162 weft	13.8±0.7	semi dull

TABLE 3: YARN PROPERTIES FOR VIRGIN PET PROSTHESES (CONTD)

Prostheses	Yarn type linear	Yarn nominal density (decitex)	Approximate filament count	Filament diameter (μm)	Delusterant level
Impra High Porosity	textured mf	210 warp p	108 warp p	12.8±0.6	semi dull
		210 warp s	108 warp s	13.2±0.8	semi dull
		105 weft	54 weft	13.7±0.6	semi dull
Chinese H. Porosity	textured mf	88 warp	20 warp	20.9±1.6	semi dull
		88 weft	20 weft	20.9±2.3	semi dull
Chinese L. Porosity	flat mf	250 warp	96 warp	15.7±0.5	semi dull
		250 weft	96 weft	15.9±1.5	semi dull
Woven Braun Melsungen	flat mf	226 warp	65 warp	17.9±0.7	semi dull
		117 weft	33 weft	18.1±0.9	semi dull
Indian	flat mf	154 warp	60 warp	15.4±2.1	semi dull
		212 weft	70 weft	16.7±1.5	semi dull
Velex	textured mf	135 warp	91 warp	11.7±1.6	semi dull
	flat weft mf	127 weft	92 weft	11.3±1.4	semi dull

Note s=satin, p=plain, l=leno, mf=multifilament, f=floats.

TABLE 4: PHYSICAL PROPERTIES OF VIRGIN WOVEN POLYESTER PROSTHESES

Prostheses	Dilation at 120 mmHg (%)	Water permeability (ml/min/cm²)	Suture Retention Strength (Newtons) 0°	90°	45°	Bursting Strength (Newtons)
Twill Woven	0.4	80	24.6	30.1	21.6	280±27
Soft Woven DeBakey	0.2	216	34.8	35.0	37.5	366±8
DeBakey EL Porosity	-	50	40.4	30.8	27.6	439±41
Woven Vascutek	0.5	89	38.9	30.7	34.5	209±1
Meadox WD Velour	2.0	395	40.9	28.6	36.6	276±4
Cooley Verisoft	0.2	181	29.9	35.7	35.2	211±13
Ochsner 200	0.5	245	21.9	39.2	29.6	268±20
Ochsner 500	1.2	530	25.5	33.9	25.9	259±8
Impra Low Porosity	0.5	312	39.8	42.8	38.0	454±13
Impra High Porosity	1.9	905	25.7	40.7	40.5	187±17
Chinese H. Porosity	-	4200	-	-	-	71±2
Chinese L. Porosity	-	94	-	-	-	407±11
Woven Bra. Melsungen	0.27	118	27.9	37.7	27.2	359±15
Indian	-	220	25.9	21.4	25.5	218
Velex	0.6	400	35.8	33.3	26.5	440

CHEMICAL PROPERTIES

TABLE 5: ESCA SURVEY SCANS SHOWING ELEMENTAL COMPOSITION ON THE SURFACES OF THE VIRGIN POLYESTER PROSTHESES EVALUATED.

Samples		C	N	O	Si	Na	S	Cl	F	Ca	Mg	Al	Zn
Twill	Internal	78.2	-	21.4	0.4	-	0.1	-	-	-	-	-	-
Woven	External	77.6	0.6	21.6	0.2	-	-	-	-	-	-	-	-
Soft Wov.	Internal	60.1	-	24.5	15.3	-	-	-	-	-	-	-	-
DeBakey	External	59.6	-	24.2	16.2	-	-	-	-	-	-	-	-
DeBakey	Internal	60.2	-	20.0	19.8	-	-	-	-	-	-	-	-
E.L.Por.	External	59.6	-	20.6	19.8	-	-	-	-	-	-	-	-
Woven Va-	Internal	85.6	-	13.6	0.3	-	-	-	0.5	-	-	-	-
scutek	External	87.2	-	12.0	0.6	0.2	-	-	-	-	-	-	-
Meadox W.	Internal	73.9	-	25.3	0.5	0.3	-	-	-	-	-	-	-
D. Velour	External	70.9	0.4	26.1	1.5	1.1	-	-	-	-	-	-	-
Meadox C.	Internal	77.1	-	22.6	-	0.2	-	-	-	-	-	-	-
Verisoft	External	75.4	1.1	21.8	0.8	0.6	0.2	0.1	-	-	-	-	-
Ochsner	Internal	75.8	-	24.0	-	-	0.2	-	-	-	-	-	-
200	External	73.5	0.4	24.6	1.2	0.2	-	-	-	-	-	-	-
Ochsner	Internal	74.8	1.2	23.2	0.6	0.1	0.1	-	-	-	-	-	-
500	External	74.5	0.9	23.7	0.7	0.2	-	-	-	-	-	-	-
Impra Low	Internal	73.7	-	24.7	1.6	-	-	-	-	-	-	-	-
Porosity	External	70.7	0.4	23.3	2.9	1.0	-	1.7	-	-	-	-	-
Impra Hi	Internal	75.9	-	23.0	0.8	0.2	-	-	-	-	-	-	-
Porosity	External	80.0	-	16.2	0.7	0.7	-	2.2	-	-	-	-	-
Chinese H	Internal	67.1	12.2	20.6	-	-	0.1	-	-	-	-	-	-
Porosity	External	68.6	10.7	20.4	0.2	-	0.1	-	-	-	-	-	-
Chinese L	Internal	87.0	0.5	13.0	0.6	0.4	-	-	-	1.3	-	-	-
Porosity	External	87.0	-	13.0	1.0	0.7	-	0.2	-	1.5	-	-	0.1
Wov Braun	Internal	74.5	0.4	25.1	-	-	-	-	-	-	-	-	-
Melsungen	External	73.5	0.4	25.4	0.1	0.2	-	0.1			0.2	-	-
Indian	Internal	69.9	1.5	26.6	1.0	0.4	0.1	0.1	-	-	0.5	-	-
	External	63.1	1.7	29.1	3.1	0.7	-	0.2	-	-	1.6	0.6	-
Velex	Internal	86.5	-	12.5	0.8	0.3	-	-	-	-	-	-	-
	External	84.7	-	14.7	0.5	-	-	0.1	-	-	-	-	-

TABLE 6: HIGH RESOLUTION ESCA SPECTRA OF C1s AND O1s FOR THE VIRGIN, WOVEN PROSTHESES ANALYSED.

		Carbon 1s peak (%)			Oxygen 1s peak (%)	
Prostheses	Surface	C-C	C-O	O-C=O	C-O	O-C=O
Twill Woven	Internal	75.7	12.3	12.0	62.5	37.5
	External	78.4	10.4	11.2	60.1	39.9
Soft Woven DeBakey	Internal	85.8	7.8	6.4	84.6	15.4
	External	86.5	7.5	6.0	89.6	10.4
DeBakey Extra L. Por.	Internal	96.8	1.8	1.4	33.8	66.2
	External	96.0	2.2	1.8	45.6	54.4
Woven Vascutek	Internal	85.9	7.2	6.9	61.2	38.8
	External	87.2	6.6	6.2	63.6	36.4
Meadox Woven D. Velour	Internal	72.3	12.1	15.6	54.1	45.9
	External	67.0	16.5	16.5	54.7	45.3
Meadox Cooley Verisoft	Internal	71.8	13.0	15.1	50.4	49.5
	External	72.3	14.3	13.4	56.8	43.2
Ochsner 200	Internal	74.9	13.4	11.6	77.9	22.1
	External	69.9	19.2	10.9	78.0	22.0
Ochsner 500	Internal	70.2	18.8	11.0	74.0	26.0
	External	76.3	13.2	10.5	76.4	23.6
Impra Low Porosity	Internal	61.7	24.6	13.7	61.2	38.8
	External	66.0	23.4	10.6	64.5	35.5
Impra High Porosity	Internal	68.8	19.9	11.3	61.3	38.7
	External	76.3	16.7	7.0	63.1	36.9
Chinese High Porosity	Internal	48.8	27.8	23.4	-	-
	External	46.8	31.6	21.6	-	-
Chinese Low Porosity	Internal	83.0	9.0	8.0	54.0	46.0
	External	82.0	10.0	8.0	56.0	44.0
Woven Braun Melsungen	Internal	66.0	20.4	13.6	65.3	34.7
	External	66.9	20.8	12.2	62.4	37.6
Indian	Internal	67.4	17.6	15.0	61.4	38.6
	External	67.1	18.3	14.6	57.9	42.1
Velex	Internal	89.8	4.6	5.6	74.7	25.3
	ExternaL	87.5	5.6	6.9	68.6	31.4

TABLE 7: DSC DATA FOR VIRGIN POLYESTER PROSTHESES.

Prostheses	Tg (°C)	Tm (°C)	▲H (J/g)	Crystallinity Index
Twill Woven	71.60±1.54	260.54	56.62	0.40
Soft Woven DeBakey	76.96±0.26	260.52	58.78	0.42
DeBakey Extra Low Porosity	76.55±0.19	258.78	60.44	0.43
Woven Vascutek	75.03±0.16	258.82	56.79	0.41
Meadox Wov. Doub. Velour	76.34±0.28	256.63	56.24	0.40
Meadox Cool. Verisoft	76.77±0.39	257.99	58.96	0.42
Ochsner 500	75.54±0.36	253.81	56.93	0.41
Impra Low Porosity	75.63±0.74	257.55	56.93	0.41
Wov. Braun Melsungen	78.55±0.15	258.02	60.38	0.43
Indian	75.84±0.83	256.17	57.83	0.41
Velex	75.75±0.56	260.03	55.27	0.39

Table 8: FTIR PEAK ASSIGNMENTS FOR THE TWILL WOVEN PROSTHESIS.

Peak (cm^{-1})	Relative Intensity	Assignment
1712	strong	C=O stretch
1577	weak	
1504	weak	
1473	weak	C=C aromatic stretch
1408	medium	CH_2 bending vibration
1341	medium	
1237	strong	O-C stretch of ester
1091	strong	O-C stretch of ester
1016	medium	
971	weak	C-C stretch of the glycol backbone in the trans conformation
896	v. weak	C-C stretch of the glycol backbone in the gauche conformation
871	weak	out of plane C-H deformation vibration (thickness band)
845	weak	C-H out of plane bending vibration

TABLE 9: LEVEL OF EXTRACTABLES FOR VIRGIN POLYESTER PROSTHESES.

Prostheses	Hexane	1,1,1-trichloro-ethane	Methanol	Water	0.1N HCl	Total
Twill Woven	0.5	0.0	0.7	0.2	0.1	1.5
Soft Woven DeBakey	0.1	0.0	0.2	0.0	0.1	0.4
DeBakey Extra Low Porosity	0.5	0.3	0.1	0.0	0.0	0.9
Vascutek Woven	0.1	0.0	0.1	0.0	0.1	0.5
Meadox Woven Double Velour	0.1	0.0	0.1	0.1	0.1	0.4
Meadox Cooley Verisoft	0.1	0.0	0.1	0.0	0.1	0.3
Ochsner 200	0.0	0.1	0.0	0.3	0.0	0.4
Ochsner 500	0.1	0.1	0.0	0.2	0.2	0.6
Impra Low Porosity	0.1	0.1	0.1	0.1	0.1	0.5
Impra High Porosity	0.1	0.0	0.1	0.1	0.1	0.4
Woven Braun Melsungen	0.0	0.0	0.5	0.0	0.0	0.5
Indian	0.0	0.0	0.4	0.6	0.2	1.2
Velex	0.0	0.0	0.1	0.2	0.1	0.4

TABLE 10: HEALING CHARTACTERISTICS OF THE PRECLOTTED TWILL WOVEN GRAFTS AFTER PRESCHEDULED DURATIONS OF IMPLANTATION OF UP TO 6 MONTHS AS THORACO-ABDOMINAL BYPASSES IN DOGS

Duration of Implantation	Graft Structure	External Capsule	Internal Capsule	Endothelium	Flow Surface
4 hours	straight	none	none	none	red in the crimps
24 hours	straight	none	none	none	red in the crimps
48 hours	straight	none	none	none	red in the crimps
1 week	straight	none	none	none	white with few reddish crimps
2 weeks	straight	thoracic region	anastomoses	yes	white with few reddish crimps
1 month	Slightly bent distally	entire graft	thin at both anastomoses	yes	white with few reddish crimps
3 months	slightly bent distally	entire graft	thin and almost complete	yes	white with few thrombi
6 months	straight	entire graft	thick and complete	yes	white with few thrombi

TABLE 11: FIBRIN AND PLATELET UPTAKE ON THE LUMINAL SURFACE OF THE PRECLOTTED TWILL WOVEN GRAFT

Duration of Implantation	Fibrin (% x 10^2)			Platelets (%)		
	Proximal	Medial	Distal	Proximal	Medial	Distal
4 hours	0.42	0.42	0.32	0.38	0.70	0.04
24 hours	0.77	1.05	0.08	0.35	0.32	0.04
48 hours	0.11	0.06	0.02	0.33	0.36	0.08
1 week	0.15	0.27	0.06	0.33	0.41	0.07
2 weeks	0.35	0.47	0.10	0.26	0.42	0.11
1 month	0.67	0.24	0.09	0.33	0.32	0.06
3 months	0.15	0.11	0.00	0.18	0.15	0.03
6 months	3.50	1.90	0.60	0.31	0.25	0.01

TABLE 12: TEXTILE\YARN PROPERTIES FOR THE EXPLANTED TWILL WOVEN GRAFTS.

length of implantation	yarn type	fabric count (cm^{-1})	filament diameter (μm)
0	warp plain	42 ± 2	13.2 ± 1.3
	warp float	22 ± 1	13.2 ± 1.3
	weft	48 ± 2	14.2 ± 1.7
3 months	warp plain	42 ± 2	13.7 ± 2.2
	warp float	22 ± 1	13.7 ± 2.0
	weft	47 ± 2	13.7 ± 2.0
6 months	warp plain	42 ± 2	13.8 ± 1.9
	warp float	22 ± 1	13.7 ± 2.1
	weft	48 ± 2	13.5 ± 1.4

TABLE 13: PHYSICAL PROPERTIES FOR THE EXPLANTED TWILL WOVEN GRAFTS

length of implantation	bursting strength (Newtons)	Number of measurements
0	280 ± 17	5
cleaned control	325 ± 17.8	4
4 hours	-	0
24 hours	310 ± 26.5	3
48 hours	-	0
1 week	340 ± 7.1	2
2 weeks	310 ± 7.1	2
4 weeks	-	0
3 months	294 ± 9.9	2
6 months	285	1

TABLE 14: DSC DATA FOR THE EXPLANTED TWILL WOVEN GRAFTS

Length of Implantation	Tg (°C)	Tm(°C)	Heat of Fusion (J/g)	Crystal-linty Index
0	71.60±1.54	260.54	56.62	0.40
cleaned control	77.94±0.06	259.77	55.86	0.40
4 hours	74.35±0.80	258.40	57.33	0.41
24 hours	77.33±0.54	258.48	56.93	0.40
48 hours	74.65±1.07	258.88	56.44	0.40
1 week	73.59±1.60	258.34	57.14	0.41
2 weeks	73.92±1.39	259.88	56.57	0.40
4 weeks	71.15±1.68	259.74	56.54	0.40
3 months	77.21±0.27	256.47	56.36	0.40
6 months	77.38±0.11	258.80	56.31	0.40

2.10. FIGURES:

1: POINT DIAGRAM AND CROSS-SECTIONAL DIAGRAM OF THE TWILL WOVEN PROSTHESIS SHOWING THE SEQUENCE OF YARN INTERLACEMENTS OF THE FIRST 12 WARP YARNS.

2: POINT DIAGRAM AND CROSS-SECTIONAL DIAGRAM SHOWING THE SEQUENCE OF YARN INTERLACEMENTS OF THE FIRST 12 WARP YARNS FOR THOSE PROSTHESES HAVING A TAFFETTA 1/1 PLAIN WEAVE CONSTRUCTION.

3: POINT DIAGRAM AND CROSS-SECTIONAL DIAGRAM OF THE MEADOX WOVEN DOUBLE VELOUR PROSTHESIS SHOWING THE SEQUENCES OF 6/4 SATIN AND 1/1 PLAIN INTERLACEMENTS OVER THE FIRST 12 WARP YARNS.

4: DIAGRAM OF THE LENO WEAVE FOUND IN THE OCHSNER PROSTHESES.

5: POINT DIAGRAM AND CROSS-SECTIONAL DIAGRAM OF THE TWO IMPRA PROSTHESES SHOWING SEQUENCES OF 3/1 SATIN AND 1/1 PLAIN INTERLACEMENTS OVER THE FIRST 12 WARP YARNS.

6: POINT DIAGRAM AND CROSS-SECTIONAL DIAGRAM OF THE CHINESE FILAMENTOUS PROSTHESIS SHOWING SEQUENCES OF 4/1 SATIN INTERLACEMENTS OVER THE FIRST 12 WARP YARNS.

7: POINT DIAGRAM AND CROSS-SECTIONAL DIAGRAM OF THE VELEX PROSTHESIS SHOWING THE SEQUENCES OF 1/5 TWILL AND 1/1 PLAIN INTERLACEMENTS OVER THE FIRST 12 WEFT YARNS.

8: SEM PHOTOMICROGRAPHS OF THE EXTERNAL AND INTERNAL SURFACES OF THE VARIOUS PROSTHESES INCLUDED IN THE STUDY.
A: TWILL WOVEN. B: SOFT WOVEN DEBAKEY. C: DEBAKEY EXTRA LOW POROSITY. D: WOVEN VASCUTEK. E: MEADOX WOVEN DOUBLE VELOUR. F: MEADOX COOLEY VERISOFT. G: INTERVASCULAR OCHSNER 200. H: INTERVASCULAR OCHSNER 500. I: IMPRA LOW POROSITY. J: IMPRA HIGH POROSITY. K: CHINESE HIGH POROSITY. L: CHINESE LOW POROSITY. M: BRAUN PROTEGRAFT LOW POROSITY. N: INDIAN. O: VELEX.

9: DIAGRAMATIC REPRESENTATION OF THE PHYSICAL PROPERTIES OF THE PROSTHESES STUDIED.
A: BURSTING STRENGTH. B: WATER PERMEABILITY. C: DILATION. D: SUTURE RETENTION STRENGTH.

10: ESCA SURVEY SCAN FOR THE VIRGIN TWILL WOVEN PROSTHESIS.

11: HIGH RESOLUTION ESCA SPECTRA OF THE VIRGIN TWILL WOVEN PROSTHESIS.
A: CARBON 1s SPECTRUM. B: OXYGEN 1s SPECTRUM.

12: REPRESENTATIVE DSC THERMOGRAMS FOR THE TWILL WOVEN PROSTHESIS.

13: A: TYPICAL FTIR-ATR SPECTRA FOR VIRGIN PET PROSTHESES ANALYSED.
B: FTIR-ATR SPECTRUM OF THE TWILL WOVEN PROSTHESIS.
C: FTIR SPECTRUM OF THE DEBAKEY EXTRA LOW POROSITY OVERLAID ON THAT OF THE TWILL WOVEN PROSTHESIS.

14: LIGHT MICROGRAPH OF STAINED SECTION (HEMATOXYLIN-EOSIN) THROUGH THE DISTAL WALL OF A TWILL WOVEN GRAFT EXPLANTED AFTER 48 HOURS SHOWING A MODERATE INFLAMMATORY REACTION. THE POLYMORPHONUCLEAR CELLS AND

LYMPHOCYTES HAD PENETRATED BETWEEN THE POLYESTER FIBRES (X2500).

15: *SEM PHOTOMICROGRAPH OF THE LUMINAL SURFACE OF A TWILL WOVEN GRAFT EXPLANTED AFTER 48 HOURS SHOWING AN EXTENSIVE FIBRIN NETWORK ENTRAPPING PLATELETS AND THE PRESENCE OF LEUCOCYTES IN THE PROXIMAL REGION (X2000).*

16. *LIGHT MICROGRAPH OF STAINED SECTION (MASSON TRICHROME) THROUGH THE WALL OF A TWILL WOVEN PROSTHESIS EXPLANTED AFTER 2 WEEKS SHOWING THE EARLY DEVELOPMENT OF A COLLAGENOUS INTERNAL CAPSULE AT THE PROXIMAL ANASTOMOSIS. NOTE THAT ENDOTHELIAL-LIKE CELLS WERE ALREADY CROSSING THE GRAFT-ARTERY JUNCTION (X2500).*

17: *LIGHT MICROGRAPH OF STAINED SECTION (MASSON TRICHROME) THROUGH THE MEDIAL WALL OF A TWILL WOVEN GRAFT EXPLANTED AFTER 3 MONTHS SHOWING THE DEVELOPMENT OF A THIN COLLAGENOUS CELLULAR INTERNAL CAPSULE OVER THE ENTIRE LENGTH OF THE GRAFT (X2500).*

18: *SEM PHOTOMICROGRAPH OF A TWILL WOVEN GRAFT EXPLANTED AFTER 3 MONTHS SHOWING A CONTINUOUS LINING OF ENDOTHELIAL-LIKE CELLS IN THE MEDIAL PORTION. A FEW ISOLATED PLATELETS WERE ALSO OBSERVED ON THE LUMINAL SURFACE (X1000).*

19: *TYPICAL FTIR-ATR SPECTRA OF VIRGIN AND CLEANED EXPLANTED GRAFTS SHOWING SOME EXTRA PEAKS ON THE EXPLANTED PROSTHESES.*

20: *HIGHLIGHT OF THE SPECTRAL MODIFICATIONS ON THE EXPLANTED AND CLEANED TWILL WOVEN GRAFTS.*
A: INFRA RED SPECTRUM OF THE TWILL WOVEN GRAFT EXPLANTED AT 6 MONTHS B: INFRA RED SPECTRUM OF THE VIRGIN TWILL WOVEN GRAFT C: (A - B) D: INFRA RED SPECTRUM OF A PHOSPHOLIPID FOR COMPARISON.

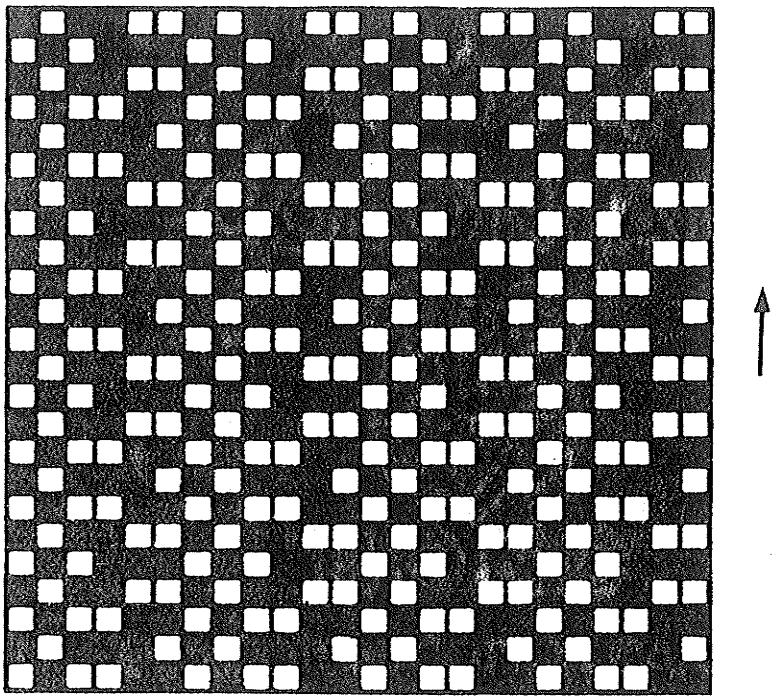


FIGURE 1A: POINT DIAGRAM OF THE TWILL WOVEN PROSTHESIS

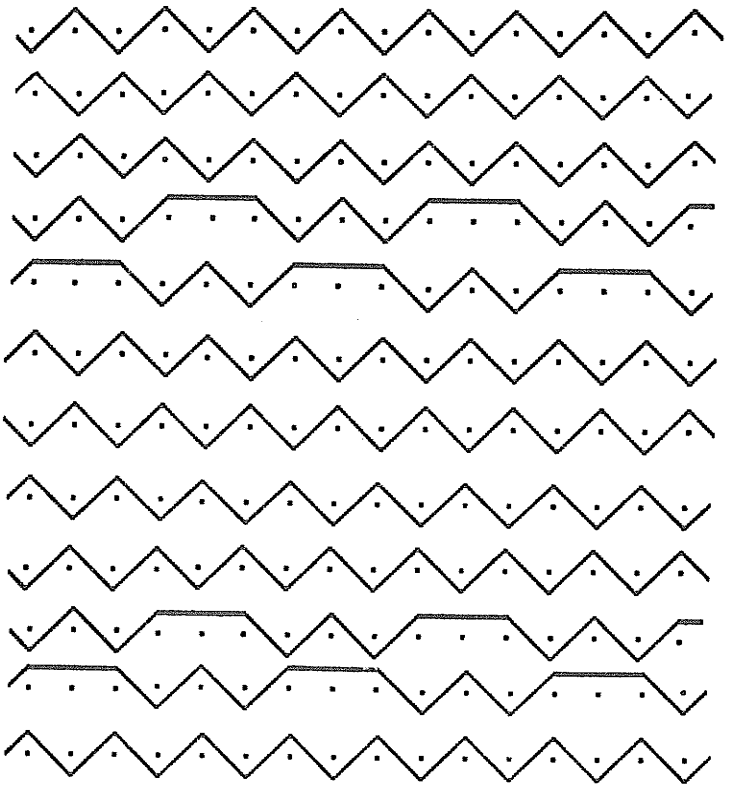


FIGURE 1B: CROSS-SECTIONAL DIAGRAM OF THE TWILL WOVEN PROSTHESIS SHOWING THE SEQUENCE OF YARN INTERLACEMENTS OF THE FIRST 12 WARP YARNS.

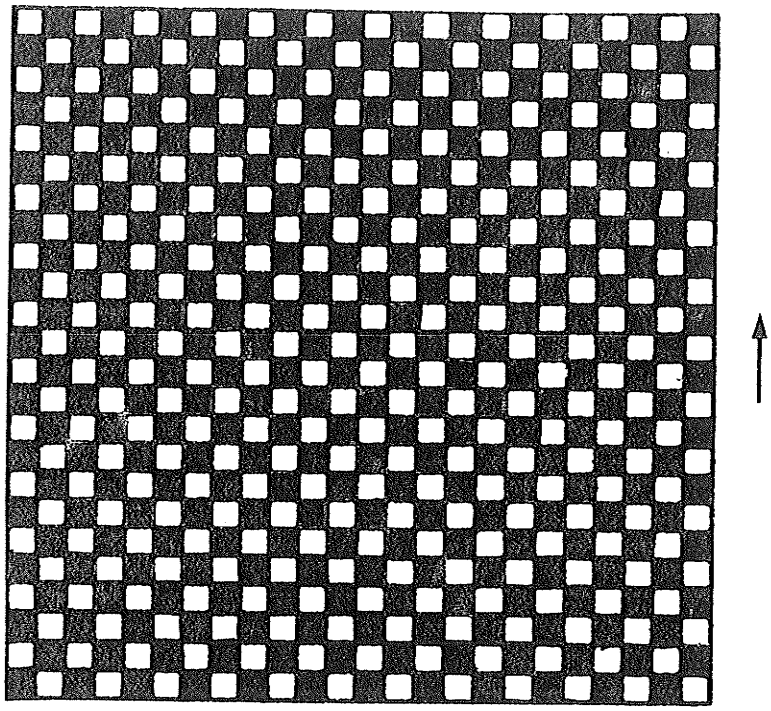


FIGURE 2A: POINT DIAGRAM FOR THOSE PROSTHESES HAVING A TAFFETTA 1/1 PLAIN WEAVE CONSTRUCTION.

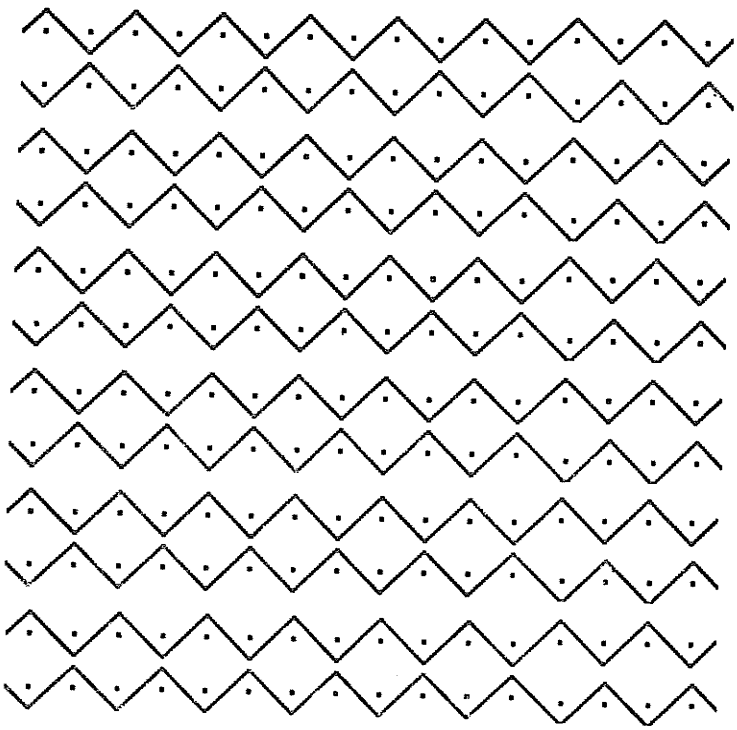


FIGURE 2B: CROSS-SECTIONAL DIAGRAM SHOWING THE SEQUENCE OF YARN INTERLACEMENTS OF THE FIRST 12 WARP YARNS FOR THOSE PROSTHESES HAVING A TAFFETTA 1/1 PLAIN WEAVE CONSTRUCTION.

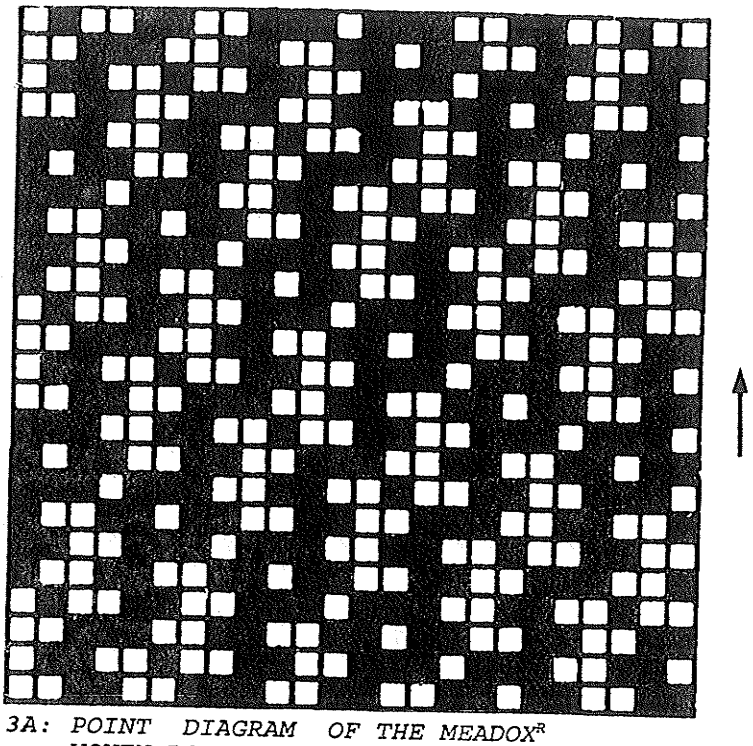


FIGURE 3A: POINT DIAGRAM OF THE MEADOX^{R} WOVEN DOUBLE VELOUR PROSTHESIS

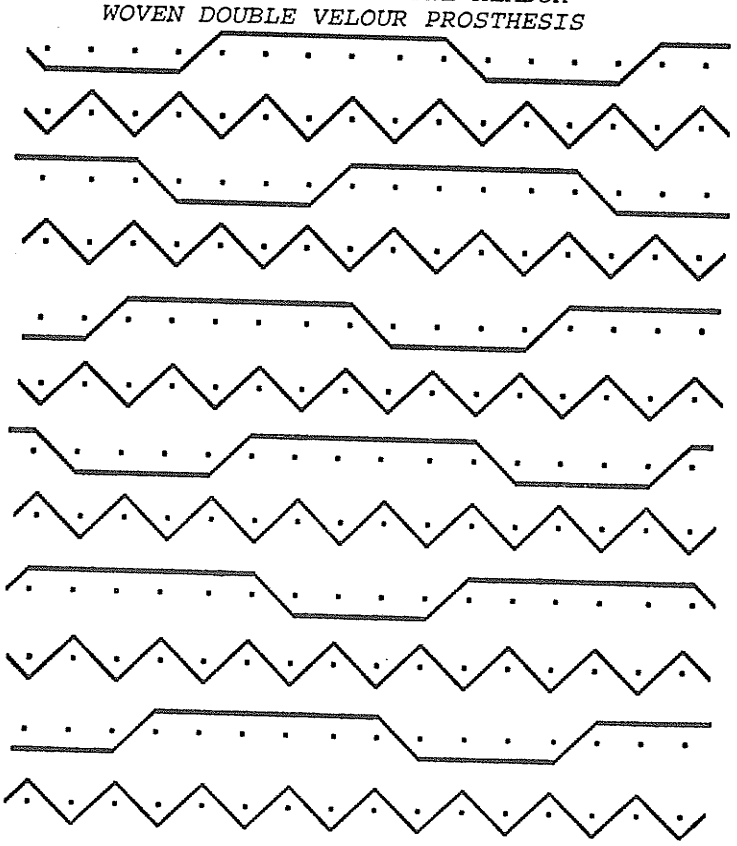


FIGURE 3B: CROSS-SECTIONAL DIAGRAM OF THE MEADOX^{R} WOVEN DOUBLE VELOUR PROSTHESIS SHOWING THE SEQUENCES OF 6/4 SATIN AND 1/1 PLAIN INTERLACEMENTS OVER THE FIRST 12 WARP YARNS.

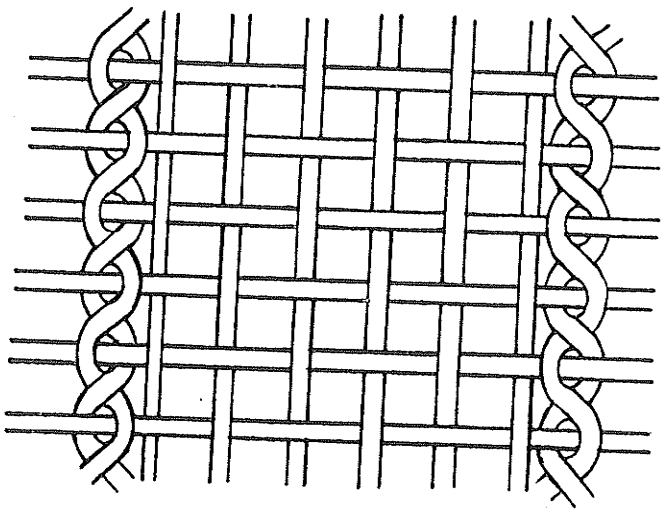


FIGURE 4 *DIAGRAM OF THE LENO WEAVE AND 1\1 PLAIN WEAVE FOUND IN THE OCHSNER PROSTHESES*

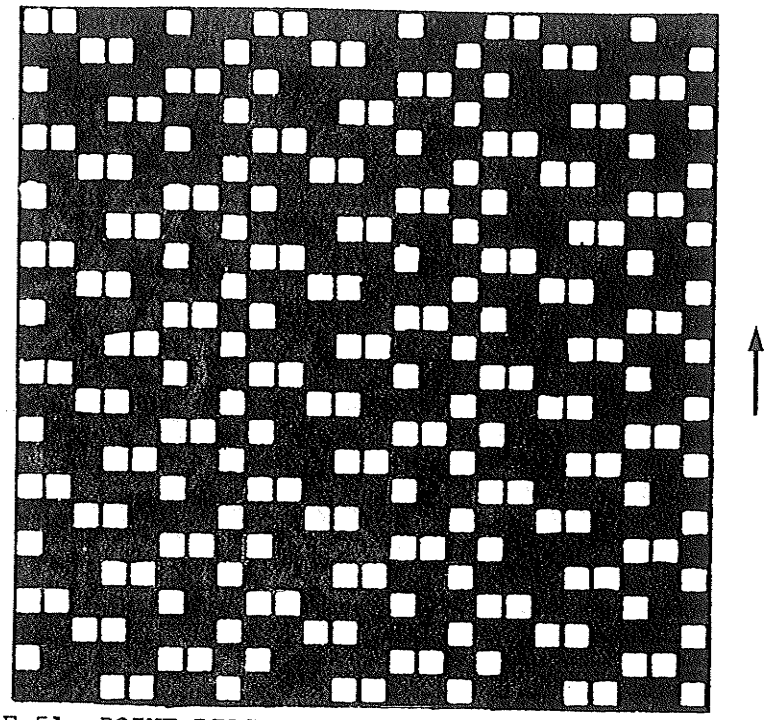


FIGURE 5A: POINT DIAGRAM OF THE TWO IMPRA PROSTHESES.

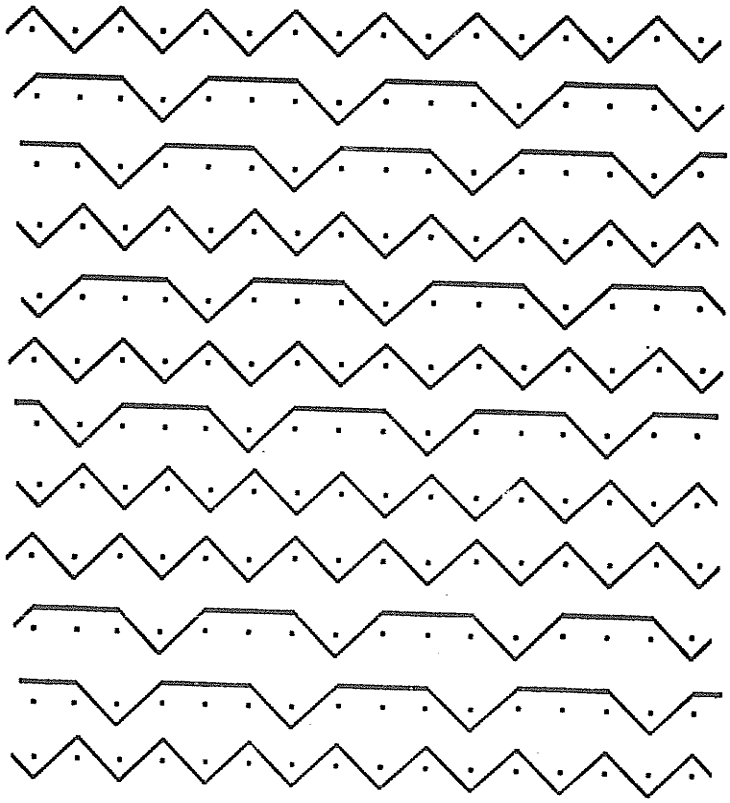


FIGURE 5B: CROSS-SECTIONAL DIAGRAM OF THE TWO IMPRA PROSTHESES SHOWING SEQUENCES OF 3/1 SATIN AND 1/1 PLAIN INTERLACEMENTS OVER THE FIRST 12 WARP YARNS.

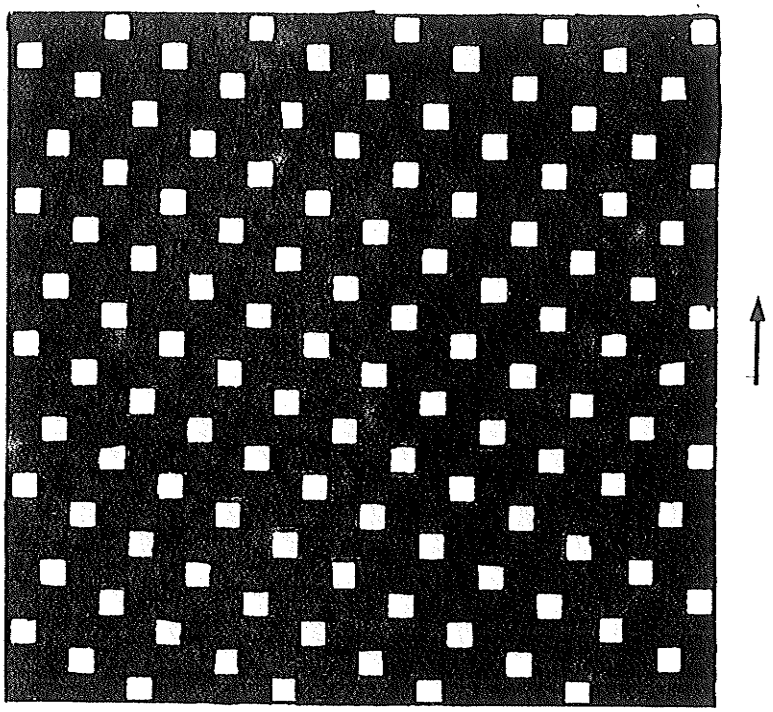


FIGURE 6A: POINT DIAGRAM OF THE CHINESE HIGH POROSITY PROSTHESIS

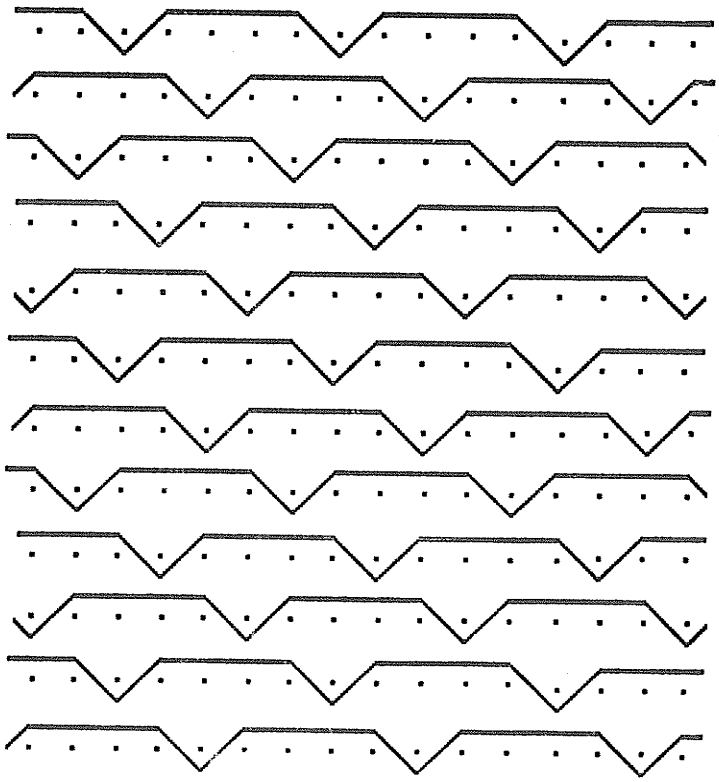


FIGURE 6B: CROSS-SECTIONAL DIAGRAM OF THE CHINESE FILAMENTOUS PROSTHESIS SHOWING SEQUENCES OF 4/1 SATIN INTERLACEMENTS OVER THE FIRST 12 WARP YARNS.

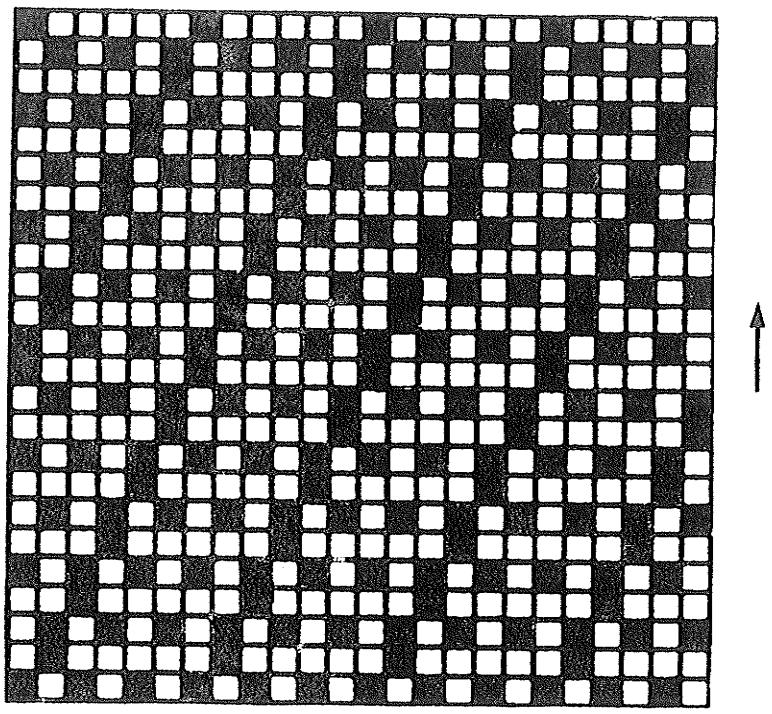


FIGURE 7A: POINT DIAGRAM OF THE VELEX PROSTHESIS

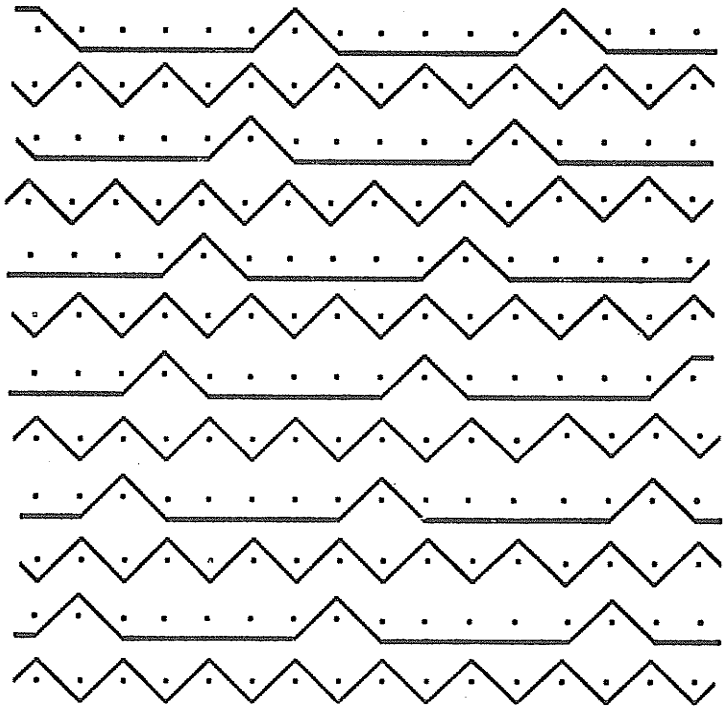


FIGURE 7B: CROSS-SECTIONAL DIAGRAM OF THE VELEX PROSTHESIS SHOWING THE SEQUENCES OF 1/5 TWILL AND 1/1 PLAIN INTERLACEMENTS OVER THE FIRST 12 WEFT YARNS.

INTERNAL

EXTERNAL

DIRECTION OF BLOOD FLOW

FIGURE 8A: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE TWILL WOVEN PROSTHESIS.

INTERNAL

EXTERNAL

FIGURE 8B: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE SOFT WOVEN DEBAKEY PROSTHESIS.

INTERNAL

EXTERNAL

DIRECTION OF BLOOD FLOW

FIGURE 8C: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE DEBAKEY EXTRA LOW POROSITY PROSTHESIS.

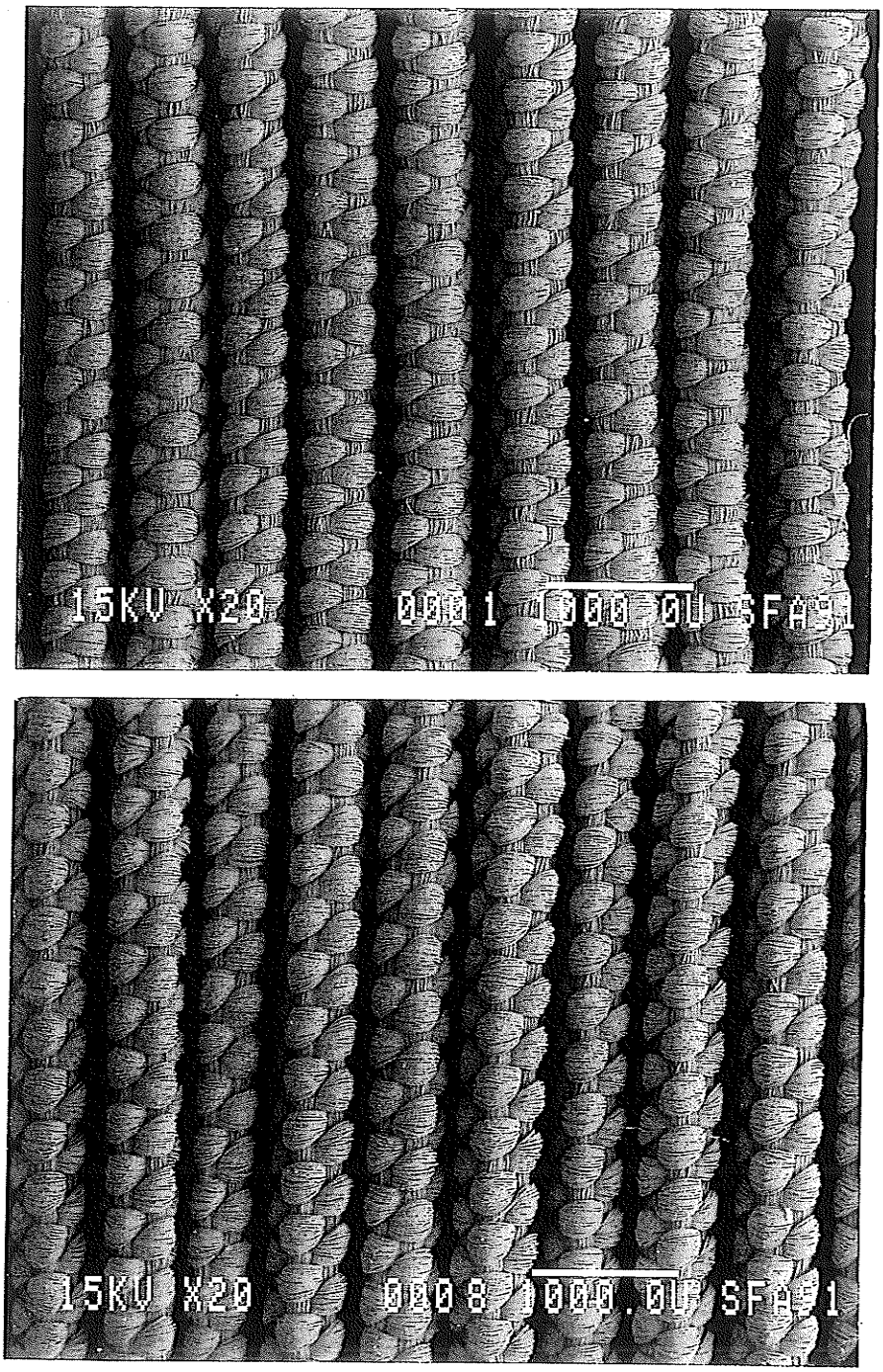
INTERNAL

EXTERNAL

DIRECTION OF BLOOD FLOW

FIGURE 8D: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE WOVEN VASCUTEK PROSTHESIS.

FIGURE 8E: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE MEADOX WOVEN DOUBLE VELOUR PROSTHESIS.



INTERNAL

EXTERNAL

DIRECTION OF BLOOD FLOW

FIGURE 8F: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE MEADOX COOLEY VERISOFT PROSTHESIS.

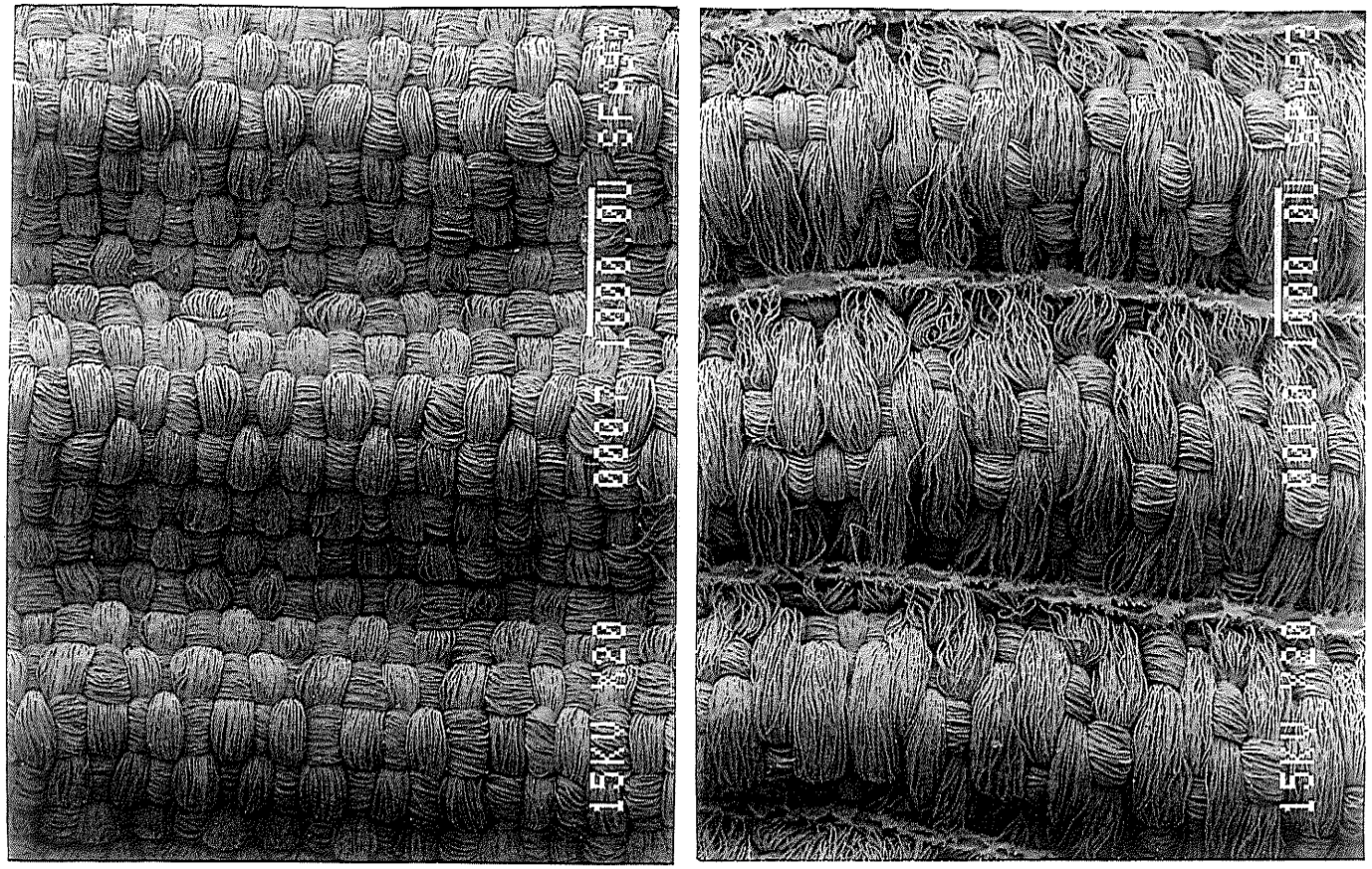
FIGURE 8G: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE INTERVASCULAR OCHSNER 200 PROSTHESIS.

INTERNAL

EXTERNAL

DIRECTION OF BLOOD FLOW

FIGURE 8H: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE INTERVASCULAR OCHSNER 500 PROSTHESIS.



INTERNAL *EXTERNAL*

FIGURE 8I: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE IMPRA LOW POROSITY PROSTHESIS.

INTERNAL

EXTERNAL

DIRECTION OF BLOOD FLOW

FIGURE 8J: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE IMPRA HIGH POROSITY PROSTHESIS.

FIGURE 8K: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE CHINESE HIGH POROSITY PROSTHESIS.

FIGURE 8L: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE CHINESE LOW POROSITY PROSTHESIS.

FIGURE 8M: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE BRAUN PROTEGRAFT LOW POROSITY PROSTHESIS.

FIGURE 8N: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE INDIAN PROSTHESIS.

FIGURE 80: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE VELEX PROSTHESIS.

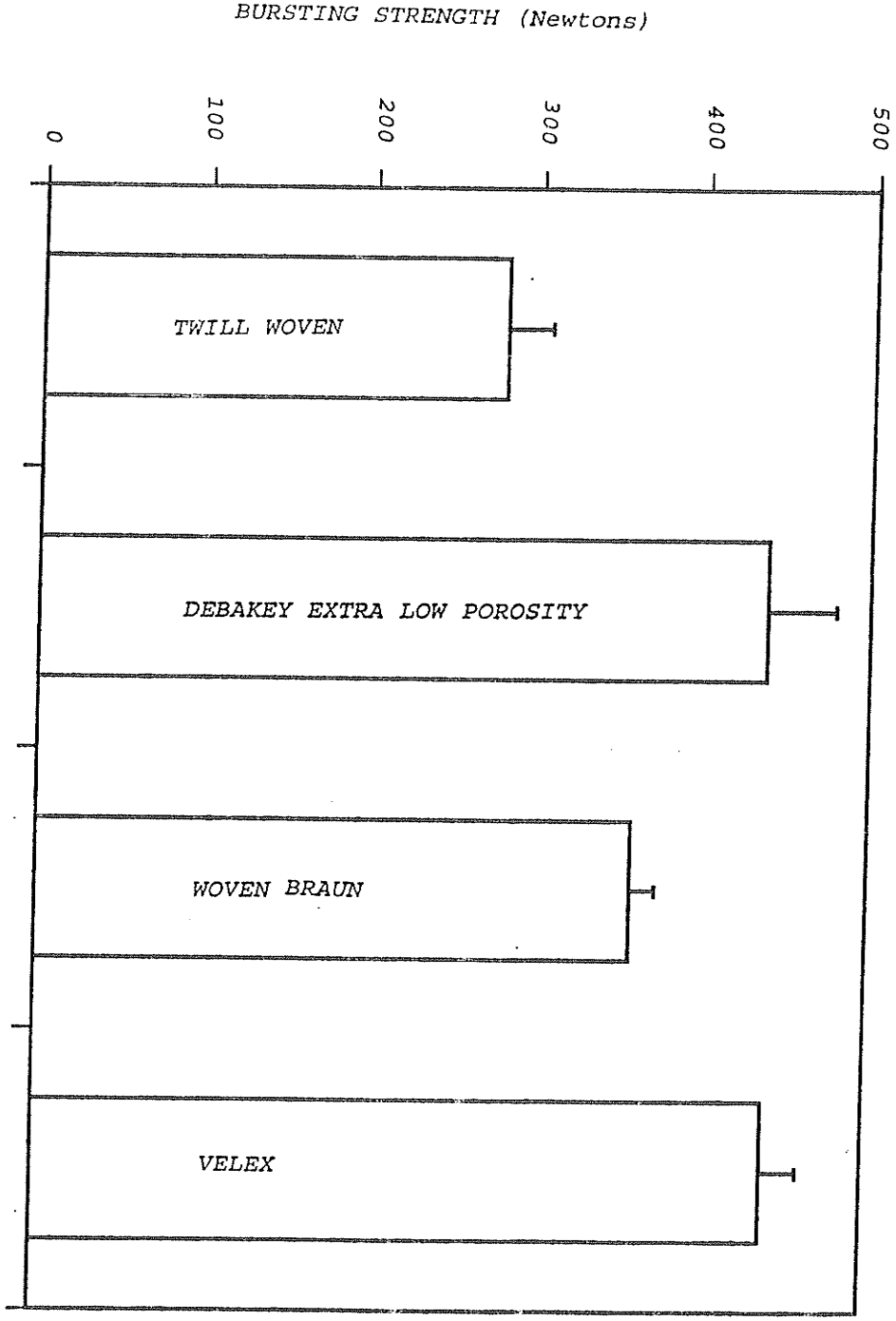


FIGURE 9A: DIAGRAMATIC REPRESENTATION OF THE BURSTING STRENGTH DATA FOR THE VARIOUS PROSTHESES STUDIED.

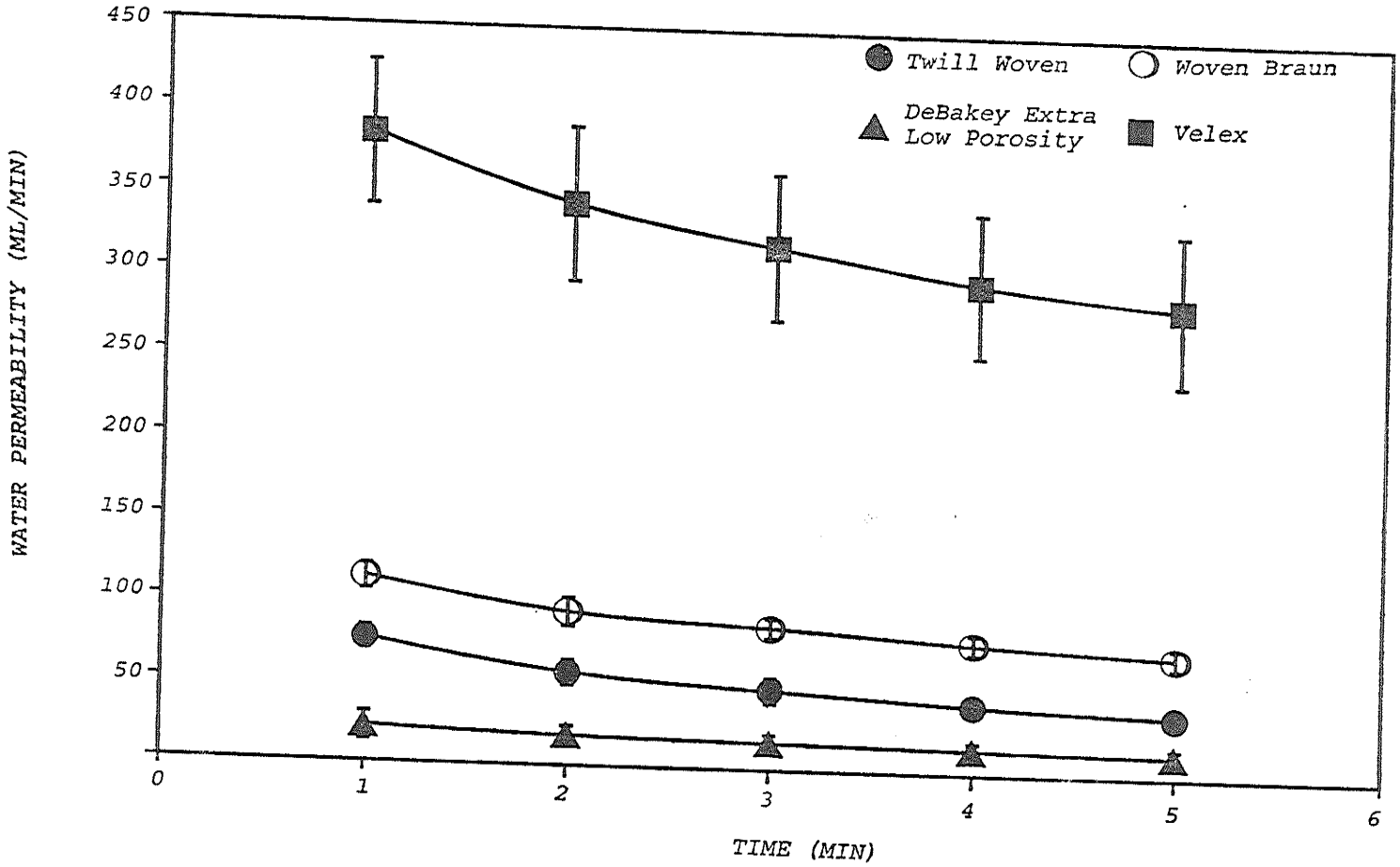


FIGURE 9B: DIAGRAMATIC REPRESENTATION OF THE WATER PERMEABILITY DATA FOR THE VARIOUS PROSTHESES STUDIED.

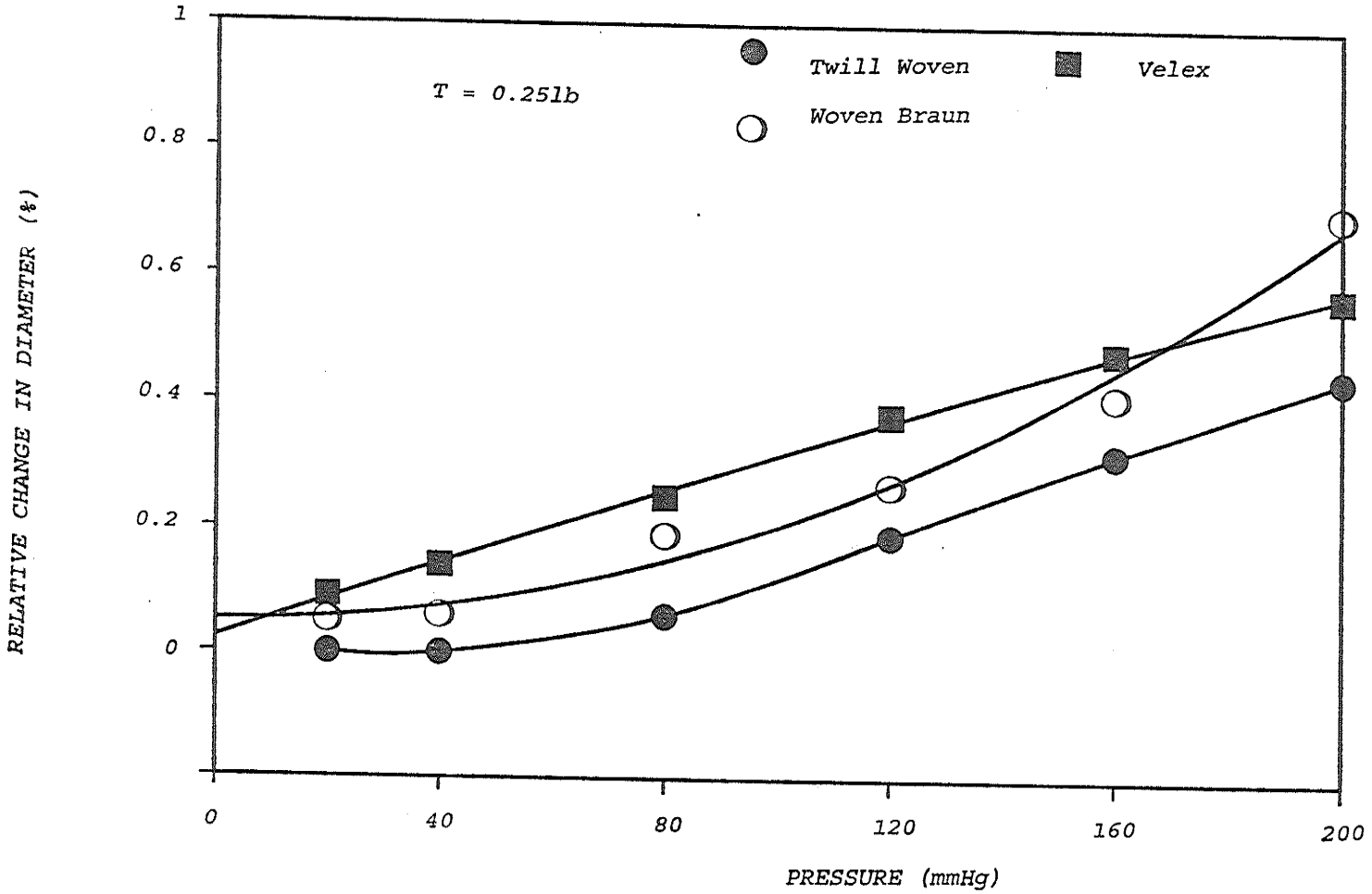


FIGURE 9C: DIAGRAMATIC REPRESENTATION OF THE DILATION DATA FOR THE VARIOUS PROSTHESES STUDIED.

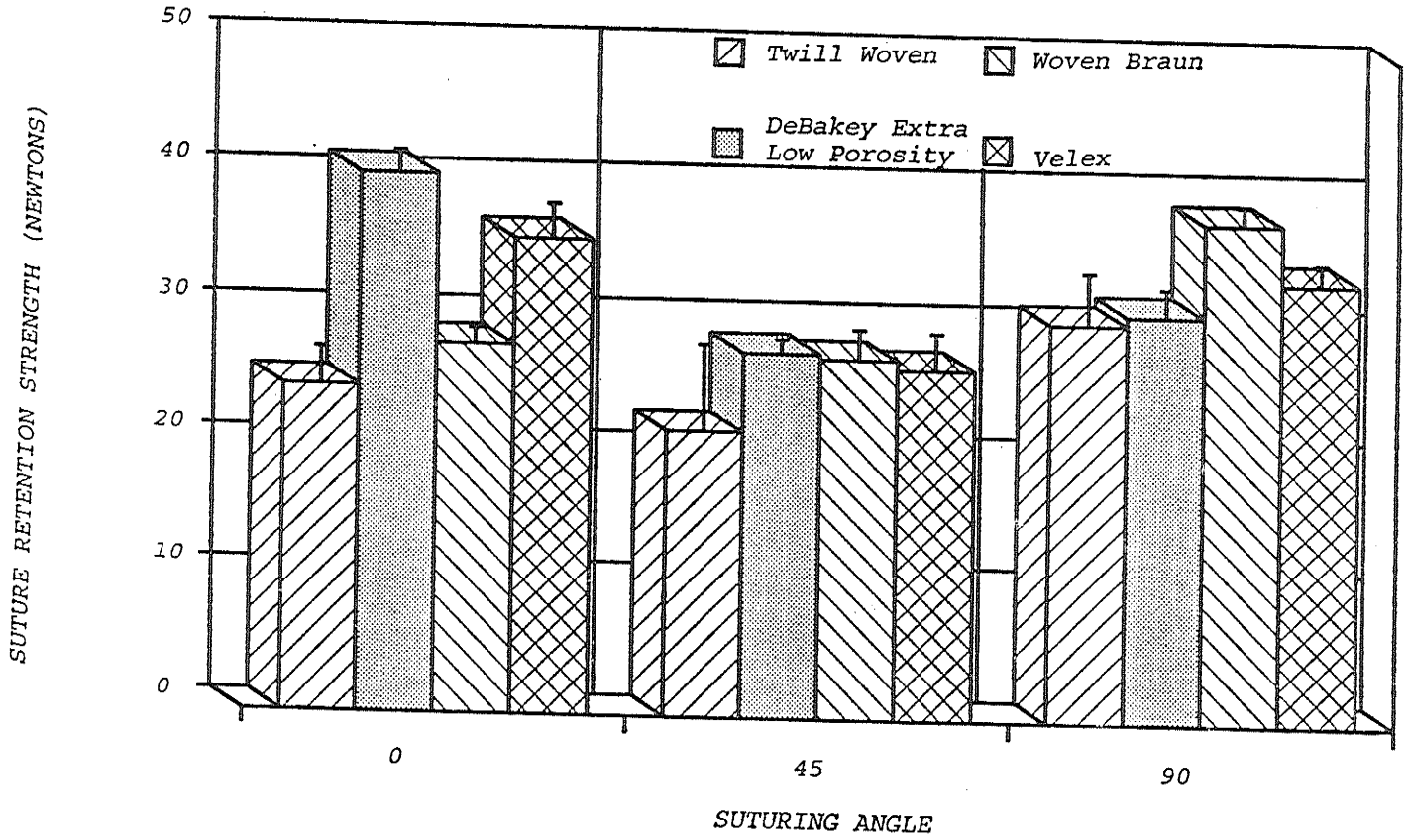


FIGURE 9D: DIAGRAMATIC REPRESENTATION OF THE SUTURE RETENTION STRENGTH DATA FOR THE VARIOUS PROSTHESES STUDIED.

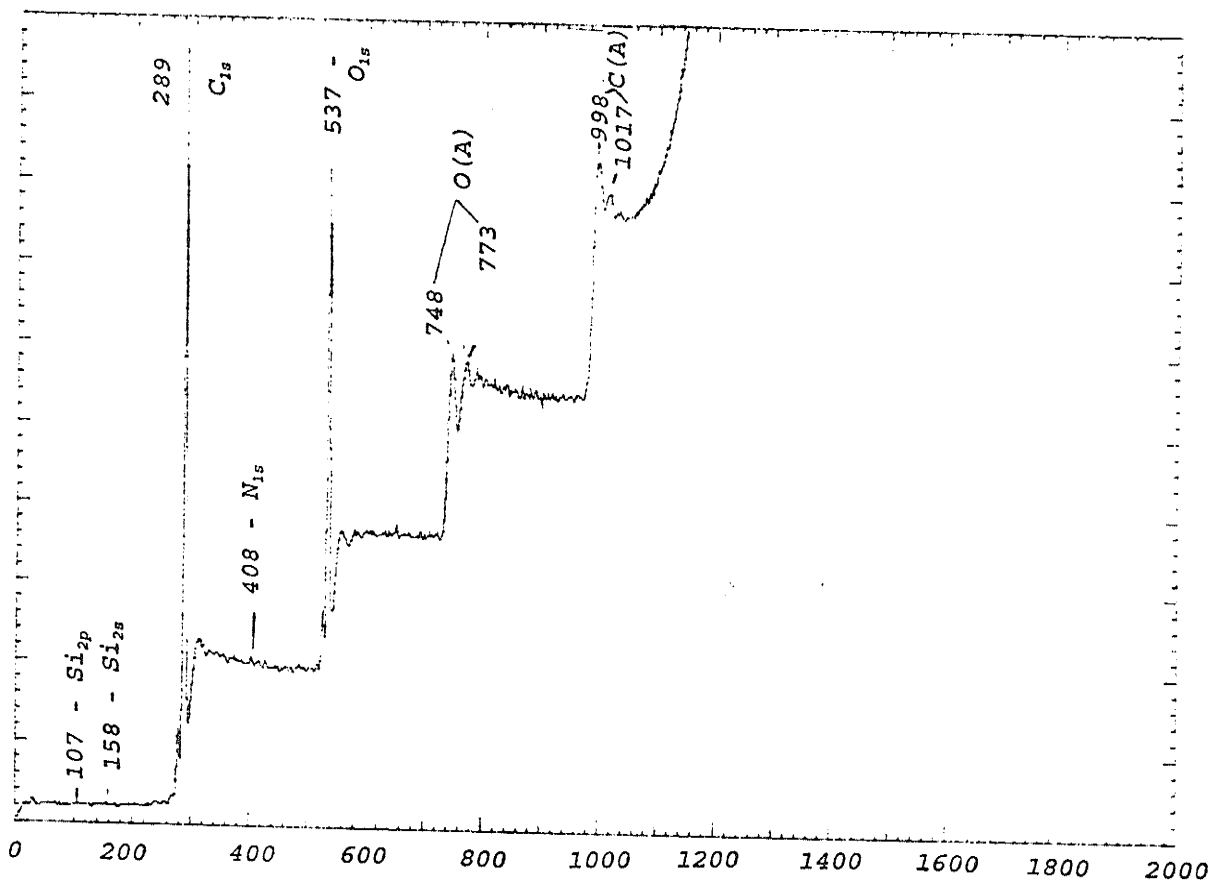


FIGURE 10: ESCA SURVEY SCAN FOR THE VIRGIN TWILL WOVEN PROSTHESIS.

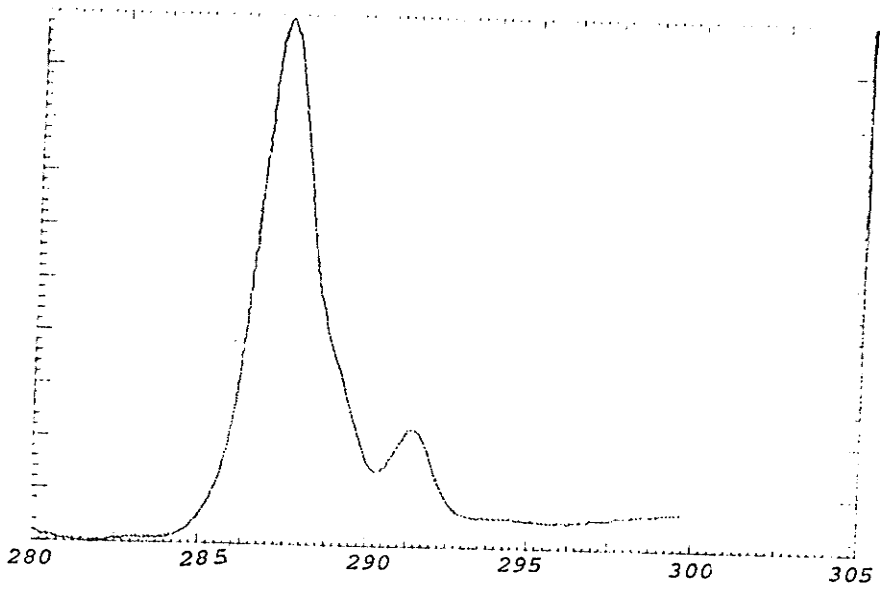


FIGURE 11A: HIGH RESOLUTION CARBON 1s ESCA SPECTRUM OF THE VIRGIN TWILL WOVEN PROSTHESIS.

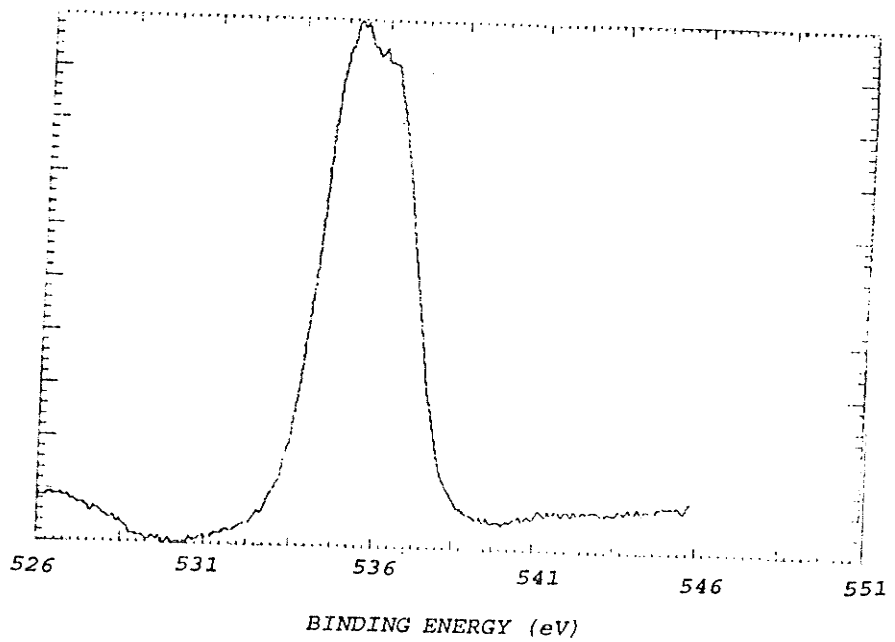


FIGURE 11B: HIGH RESOLUTION OXYGEN 1s ESCA SPECTRUM OF THE VIRGIN TWILL WOVEN PROSTHESIS.

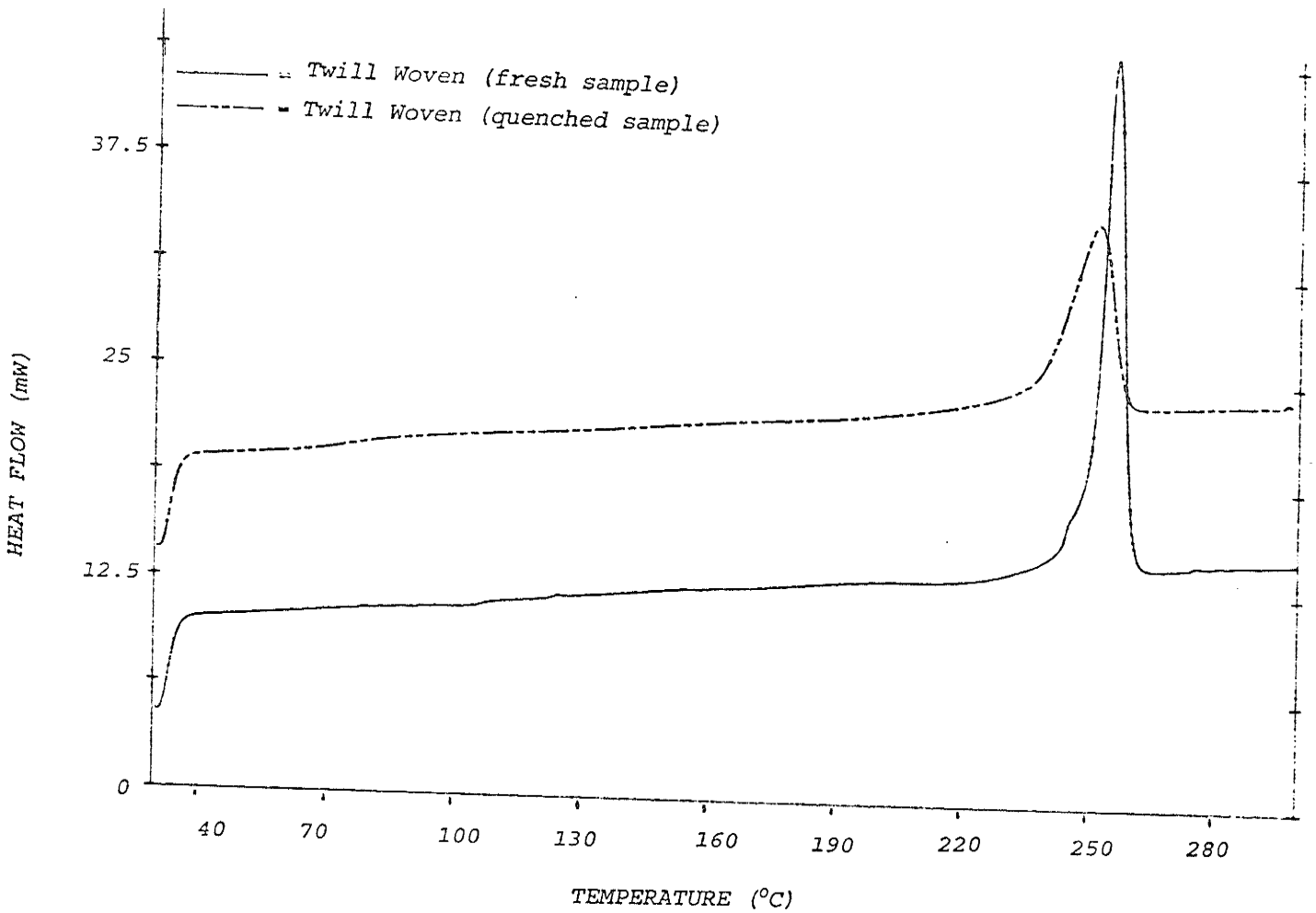


FIGURE 12: REPRESENTATIVE DSC THERMOGRAMS FOR THE TWILL WOVEN PROSTHESIS.

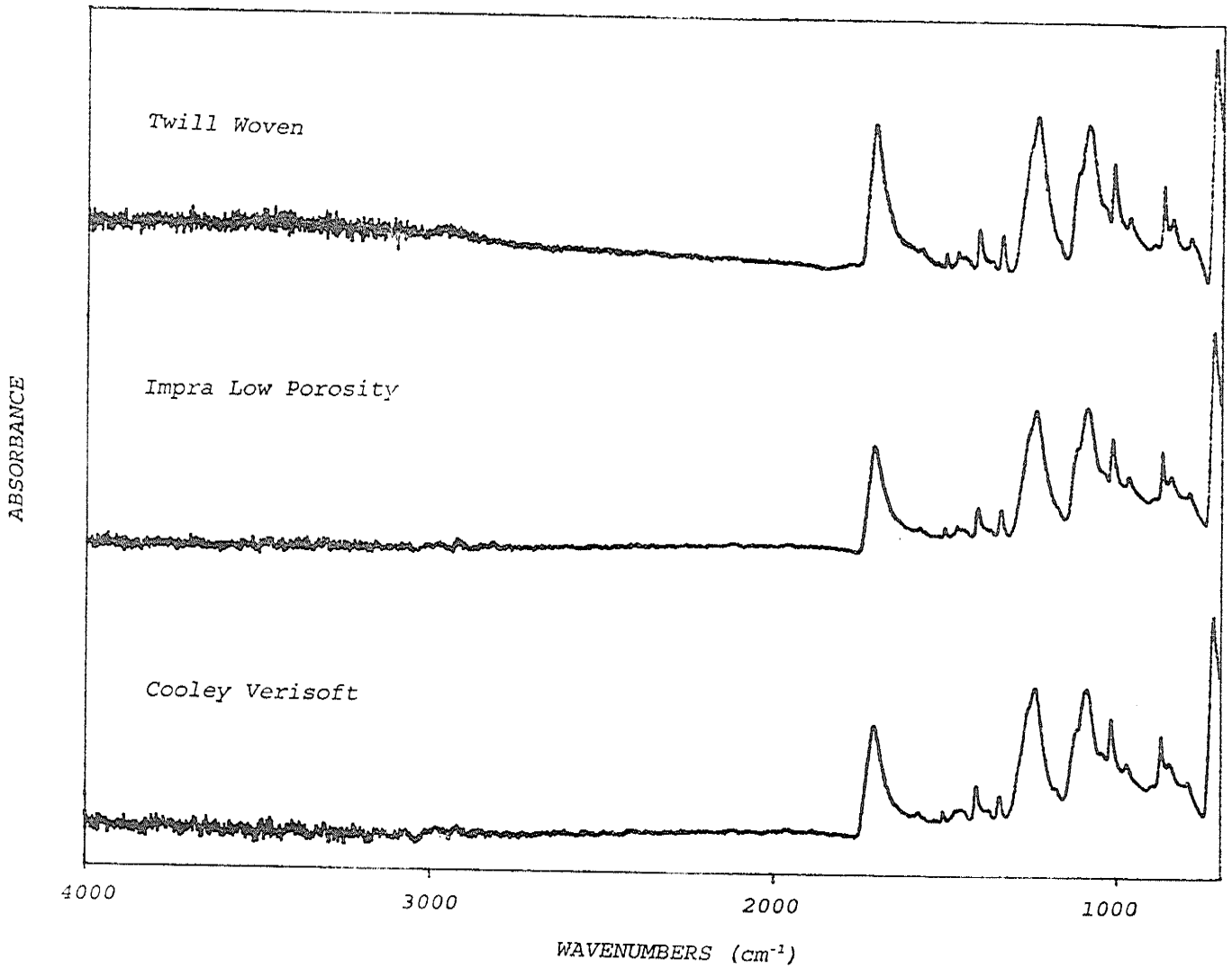


FIGURE 13A: TYPICAL FTIR-ATR SPECTRA FOR VIRGIN PET PROSTHESES ANALYSED.

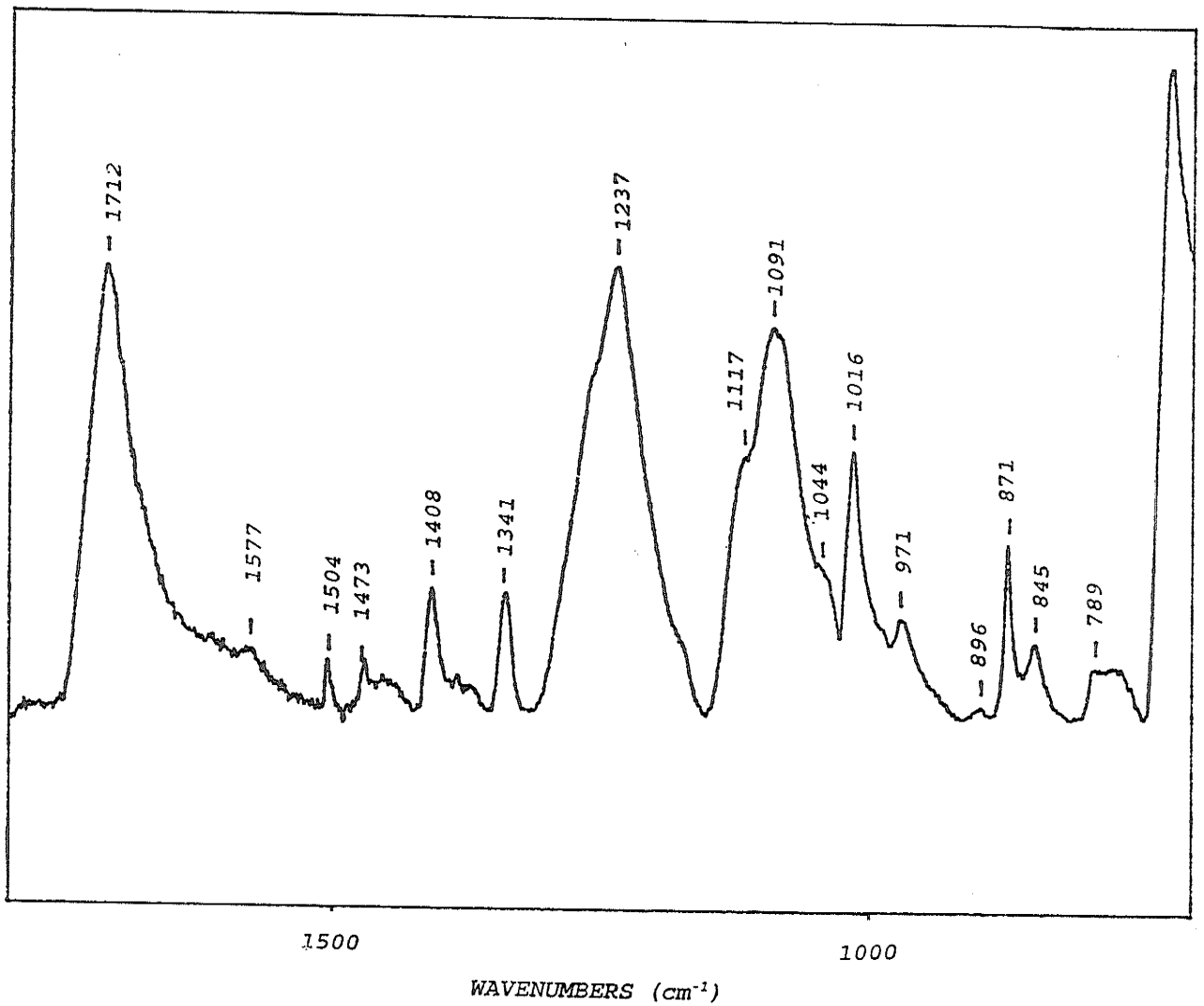


FIGURE 13B: FTIR-ATR SPECTRUM OF THE TWILL WOVEN PROSTHESIS.

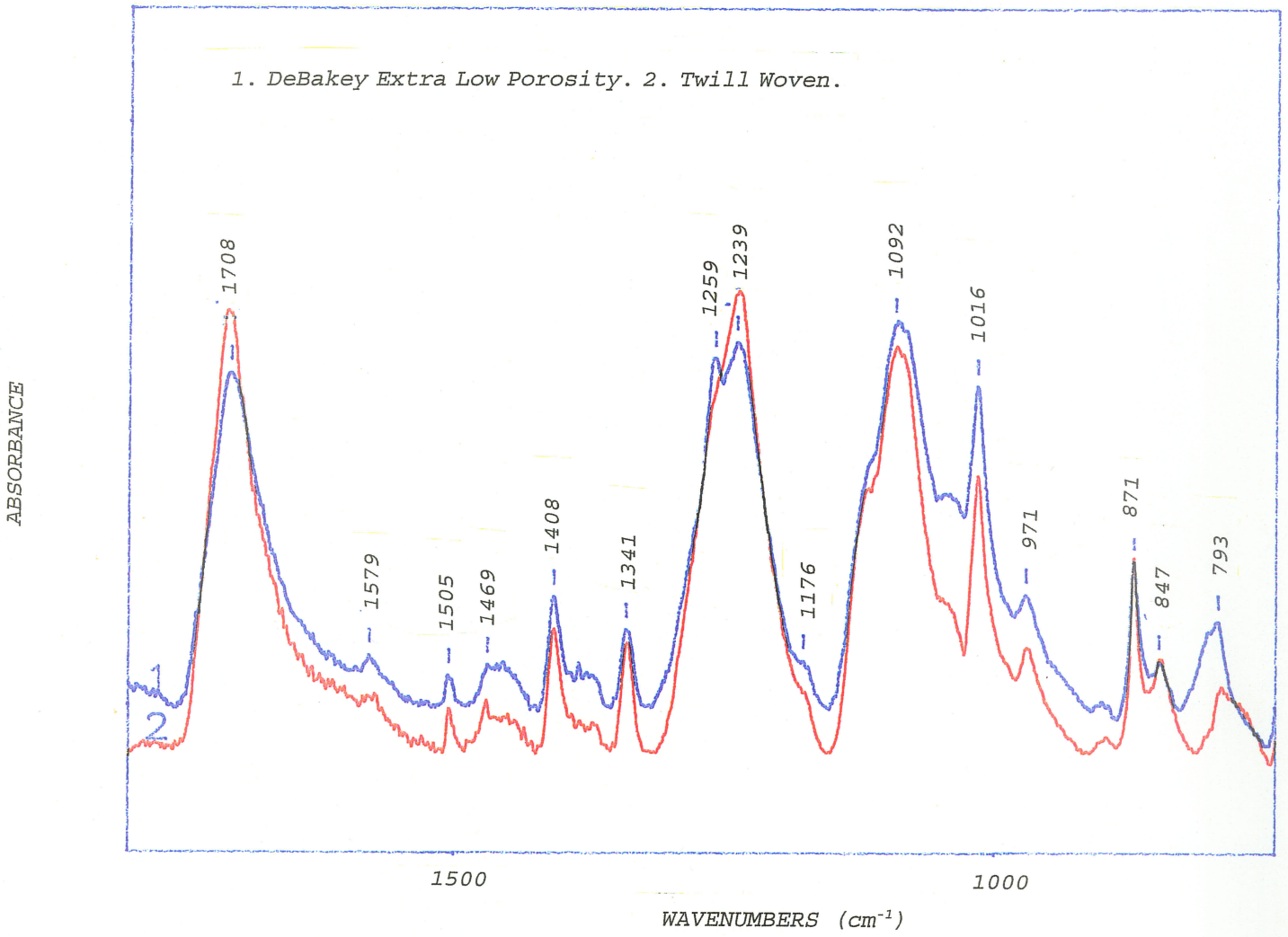


FIGURE 13C: FTIR SPECTRUM OF THE DEBAKEY EXTRA LOW POROSITY OVERLAID ON THAT OF THE TWILL WOVEN PROSTHESIS.

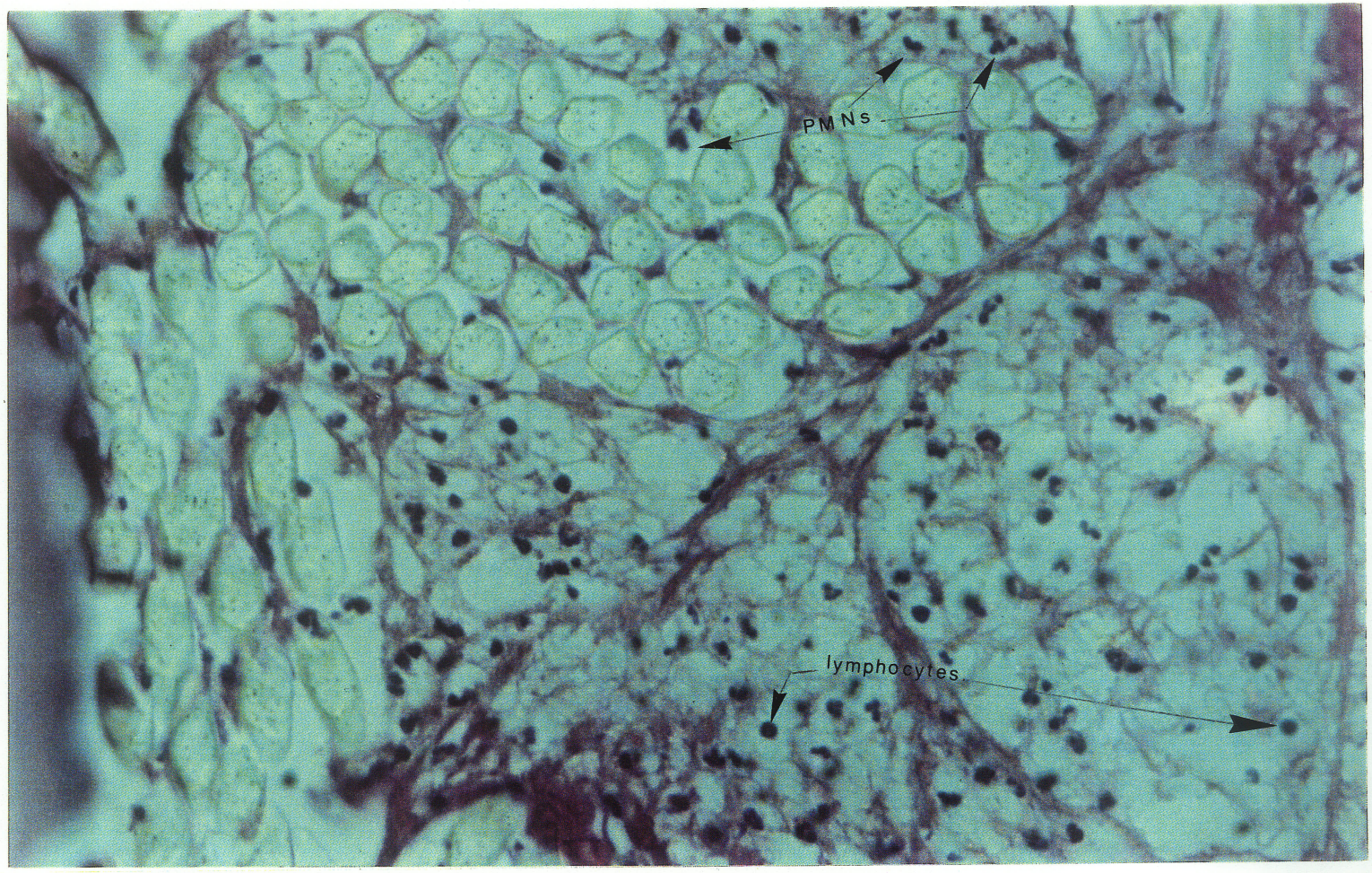


FIGURE 14: LIGHT MICROGRAPH OF STAINED SECTION (HEMATOXYLIN-EOSIN) THROUGH THE DISTAL WALL OF A TWILL WOVEN GRAFT EXPLANTED AFTER 48 HOURS SHOWING A MODERATE INFLAMMATORY REACTION. THE POLYMORPHONUCLEAR CELLS AND LYMPHOCYTES HAD PENETRATED BETWEEN THE POLYESTER FIBRES (X2500).

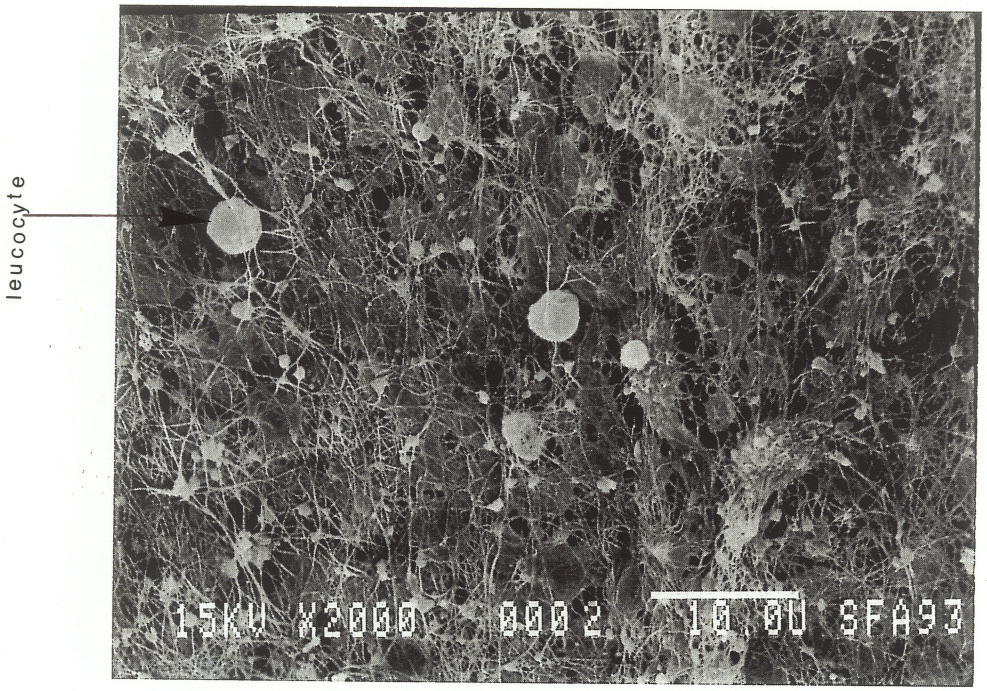


FIGURE 15: SEM PHOTOMICROGRAPH OF THE LUMINAL SURFACE OF A TWILL WOVEN GRAFT EXPLANTED AFTER 48 HOURS SHOWING AN EXTENSIVE FIBRIN NETWORK ENTRAPPING PLATELETS AND THE PRESENCE OF LEUCOCYTES IN THE PROXIMAL REGION (X2000).

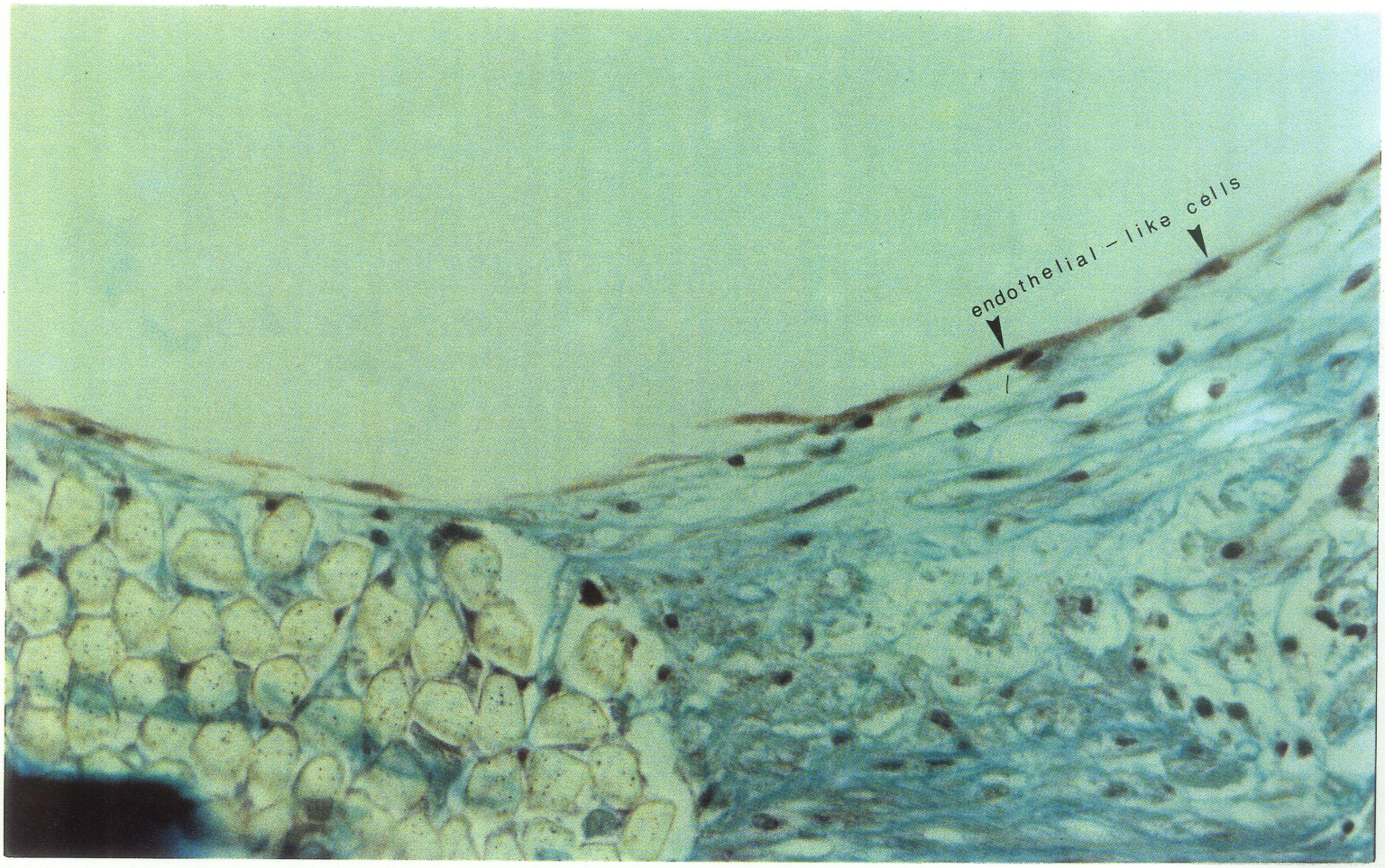


FIGURE 16: LIGHT MICROGRAPH OF STAINED SECTION (MASSON TRICHROME) THROUGH THE WALL OF A TWILL WOVEN PROSTHESIS EXPLANTED AFTER 2 WEEKS SHOWING THE EARLY DEVELOPMENT OF A COLLAGENOUS INTERNAL CAPSULE AT THE PROXIMAL ANASTOMOSIS. NOTE THAT ENDOTHELIAL-LIKE CELLS WERE ALREADY CROSSING THE GRAFT-ARTERY JUNCTION (X2500).

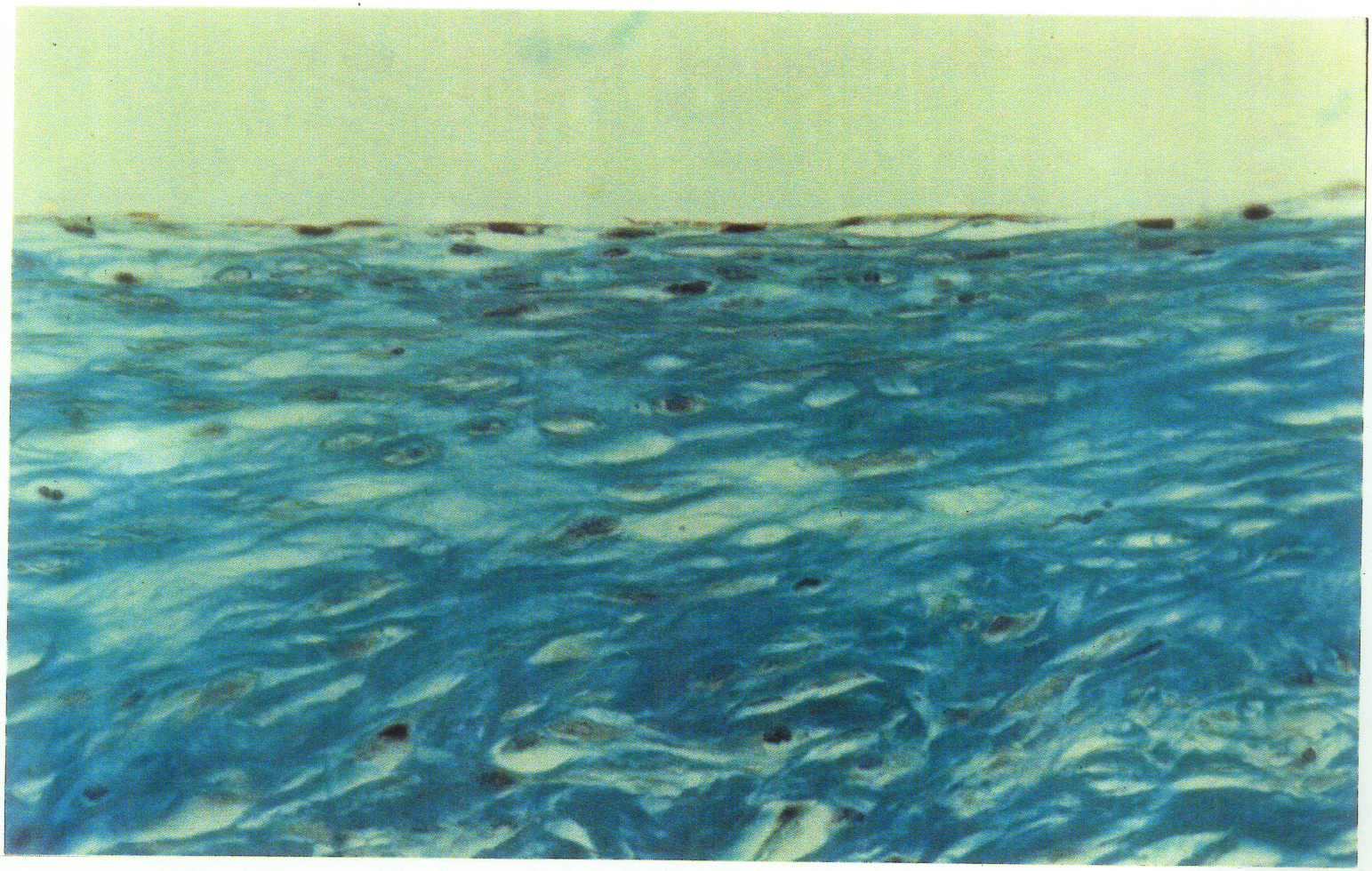


FIGURE 17: LIGHT MICROGRAPH OF STAINED SECTION (MASSON TRICHROME) THROUGH THE MEDIAL WALL OF A TWILL WOVEN GRAFT EXPLANTED AFTER 3 MONTHS SHOWING THE DEVELOPMENT OF A THIN COLLAGENOUS CELLULAR INTERNAL CAPSULE OVER THE ENTIRE LENGTH OF THE GRAFT (X2500).

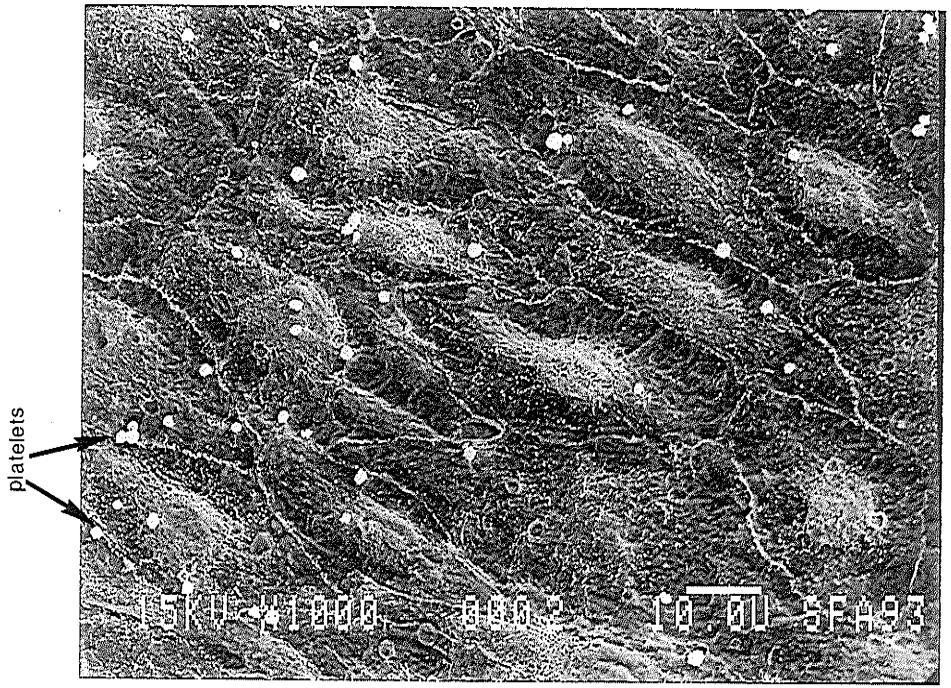


FIGURE 18: SEM PHOTOMICROGRAPH OF A TWILL WOVEN GRAFT EXPLANTED AFTER 3 MONTHS SHOWING A CONTINUOUS LINING OF ENDOTHELIAL-LIKE CELLS IN THE MEDIAL PORTION. A FEW ISOLATED PLATELETS WERE ALSO OBSERVED ON THE LUMINAL SURFACE (X1000).

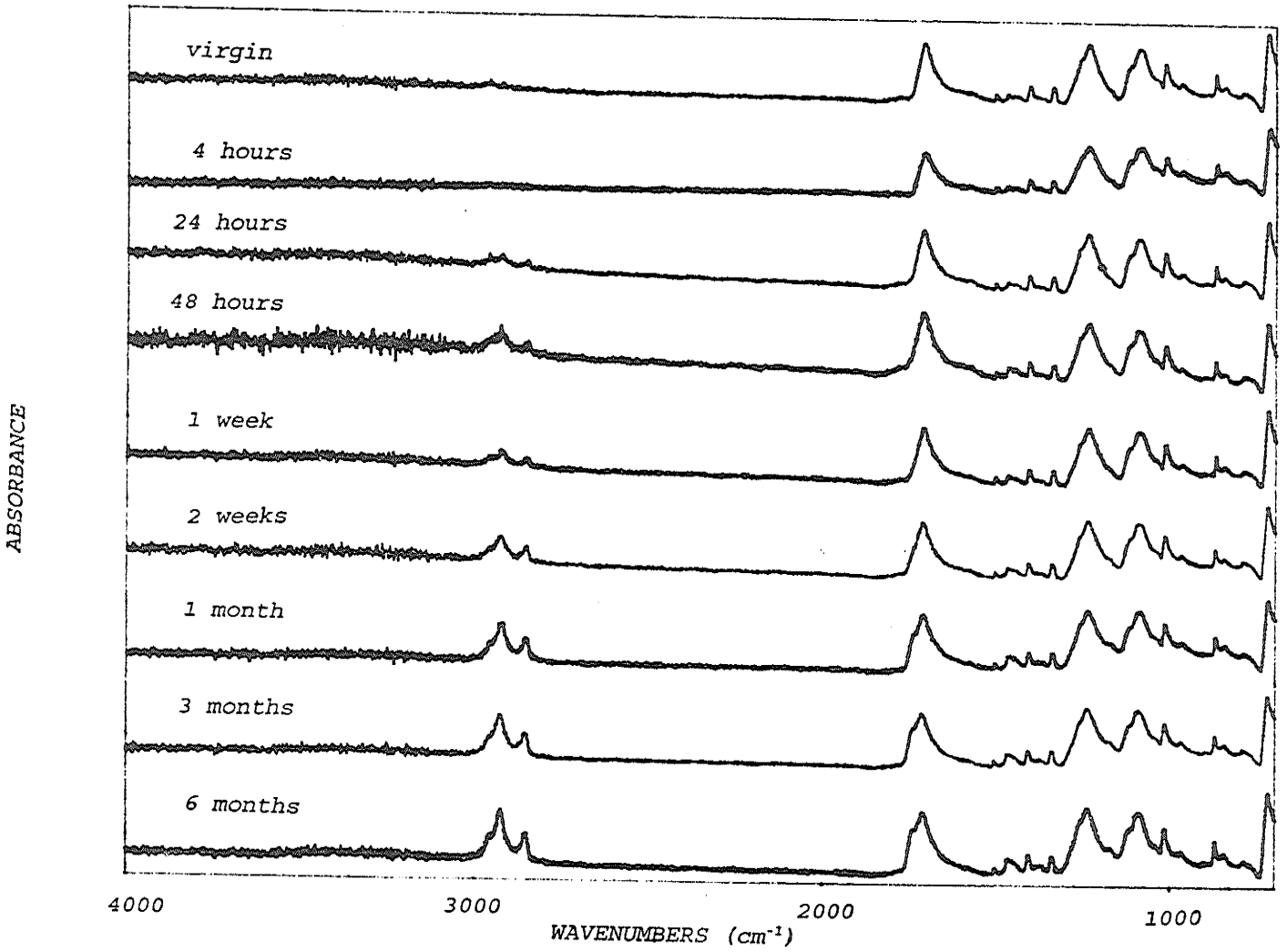


FIGURE 19: TYPICAL FTIR-ATR SPECTRA OF VIRGIN AND CLEANED EXPLANTED GRAFTS SHOWING SOME EXTRA PEAKS ON THE EXPLANTED PROSTHESES.

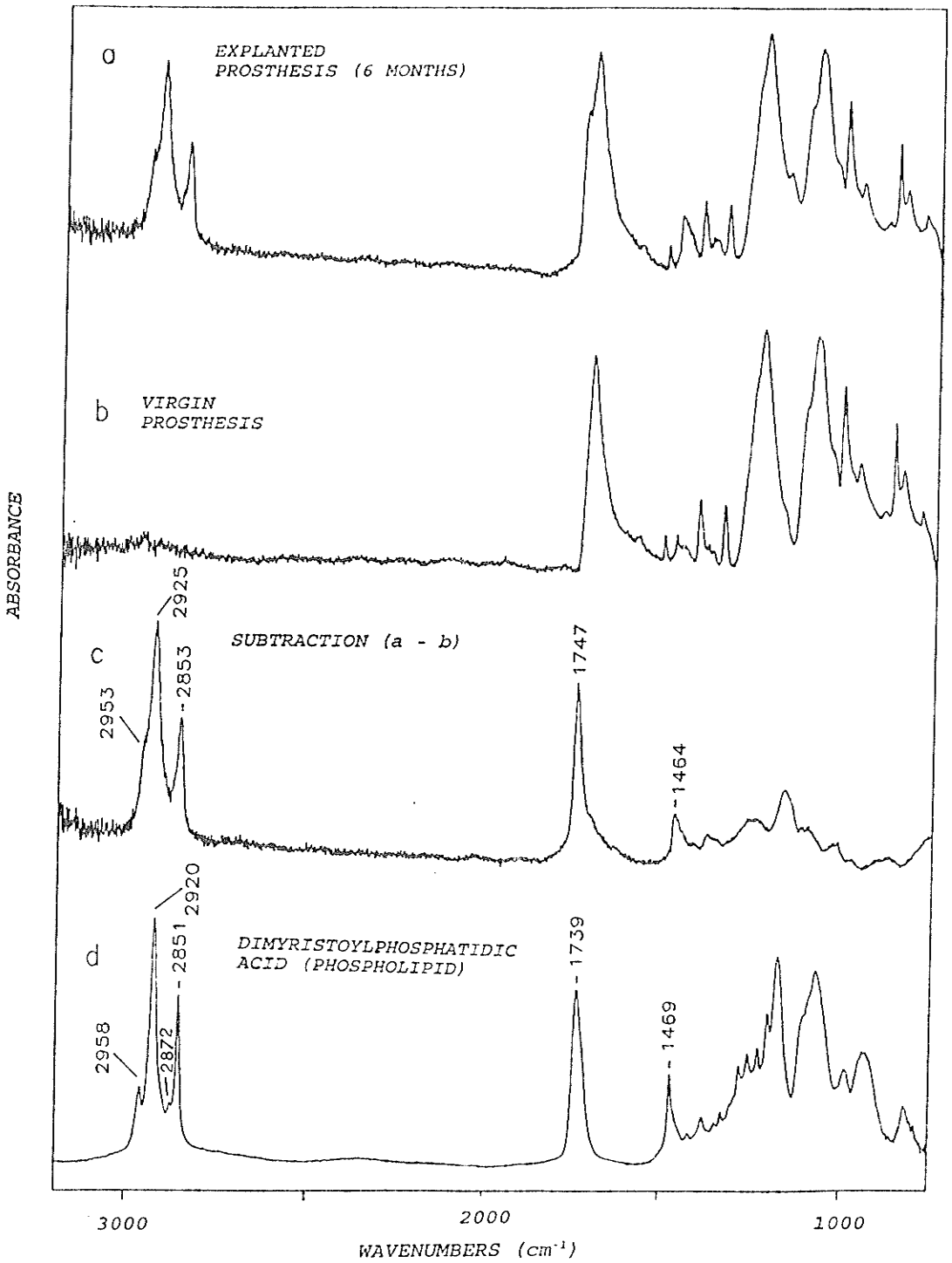


FIGURE 20: HIGHLIGHT OF THE SPECTRAL MODIFICATIONS ON THE EXPLANTED AND CLEANED TWILL WOVEN GRAFTS.

3. THE SEALED TWILL WOVEN PROSTHESIS.

3.1. INTRODUCTION:

In the search for the ideal vascular prosthesis, Vascutek Limited, a manufacturer of medical devices in Inchinnan, Scotland, UK, has recently developed a new prototype, Twill Woven prosthesis intended for use as an arterial substitute. In order to control blood seepage at implantation while maintaining a high healing capacity in the long run, Vascutek has coated the surface of the Twill Woven prosthesis with gelatin, a resorbable, biological sealant, to render the prosthesis impermeable to blood and ready to implant without preclotting. The sealant is expected to degrade slowly after implantation so that tissue ingrowth and prosthesis encapsulation can occur. However, the new product can not be placed on the market until a notice of compliance has been issued by a regulatory agency like the Bureau of Radioprotection and Medical Devices or the Food and Drug Administration. These agencies require testing (in vivo and in vitro) of the new prosthesis.

This study was undertaken to compare the in-vitro characteristics of the new prototype sealed Twill to those of the unsealed Twill Woven prosthesis and other collagen or gelatin sealed poly(ethylene terephthalate) polyester prostheses. In addition, the in-vivo biostability and biofunctionality of the sealed Twill Woven vascular prosthesis was evaluated by implanting segments of the prosthesis as thoraco-abdominal bypasses in dogs for periods ranging from 4 hours to 6 months.

3.2. MATERIALS AND METHODS:

3.2.1. Graft selection:

In addition to the unsealed and sealed Twill Woven vascular prostheses, three other sealed prostheses were selected as controls for the properties of the coating. These include the gelatin-coated Gelseal^{R}

prosthesis[1] and the collagen-coated Hemashield[R] Microvel[R] Double Velour knitted[2] and Hemashield[R] Woven Double Velour[3] vascular grafts (Table 1). The structures of these prostheses have been described in the references cited above.

3.2.2. Methods:

The in vitro and in vivo test methods utilized in this study have been described in chapter 2. In addition to these, the properties of the gelatin coating were studied using the protocols described below. ESCA and DSC techniques do not give reproducible results with sealed prostheses and were, therefore, not utilized in the analyses of such grafts.

3.2.2.1. Surface morphology:

Scanning electron microscopy was used to observe the surface morphologies of the prostheses. Small samples, mounted on stubs, were exposed to osmium tetroxide vapours, then coated with gold-palladium to improve their conduction and examined under a Jeol JSM-35CF scanning electron microscope (Soquelec, Montreal, Québec, Canada) at an accelerating voltage of 15 kV. Photographs of the surfaces of the prostheses were taken to obtain some information on the quality and evenness of the coating.

3.2.2.2. Weight of coating:

A one cm long segment of the sealed prosthesis was freeze-dried, weighed and boiled in 5% sodium bicarbonate solution for 3 minutes and allowed to cool to room temperature. The specimen was then rinsed in distilled water and subsequently immersed in 3% sodium hypochlorite solution at room temperature to remove the coating. This was followed by a final rinse in distilled water, freeze-drying and weighing to determine

the amount of coating that had been removed from the prosthesis. Measurements obtained for five segments taken from each prosthesis were averaged to give the weight of coating per gram of prosthesis.

3.3. RESULTS:

3.3.1. In vitro evaluation:

3.3.1.1. Morphology:

Figure 1 shows SEM photographs of the internal and external surfaces of the prostheses studied. The gelatin coating on the sealed Twill prosthesis seemed to be even in most places. A few cracks were, however, observed on both surfaces. Cracks were also evident on the surfaces of the sealed controls.

3.3.1.2. Textile Properties:

Table 2 shows the textile properties of the prostheses examined. The sealed Twill Woven prosthesis differs from the unsealed control only in having a gelatin sealant. This caused some increase (0.07 mm) and (93 g m^{-2}) in the fabric thickness and mass per unit area respectively of the sealed Twill variety over the unsealed prototype. With the sealed control prostheses, there were variations in fabric thickness and mass per unit area values which could not be attributed only to the differences in type/weight of coating on individual prostheses. The fabric construction and yarn properties varied from one prosthesis to another and will be reviewed briefly for each prosthesis.

The Twill Woven prosthesis is a modified plain woven structure incorporating two sets of 3/1/1/1 warp floats in every six warp ends on its external surface and a 1/1 plain woven construction on its internal surface (Figure 2a). It has a fabric count of (42p + 22f) ends x 48 weft yarns per square centimetre of fabric and was fashioned out of flat

multifilament yarns having nominal linear density values between 102 and 118 decitex. The filament diameters ranged from 13.2 to 14.2 μm (Table 3). The sealed variety was coated with gelatin.

The Gelseal^{R} prosthesis, on the other hand, is a 2-bar reverse locknit fabric with open cord laps (Figure 2b) having a stitch density of 12 wales x 16 courses cm^{-2} of fabric (Table 2). It is thicker (0.65 mm) than the sealed Twill Woven (0.40 mm), has a higher mass per unit area (658 g m^{-2}) and was fashioned out of thicker, texturized yarns (Table 3) (almost 2x the nominal linear density of the yarns found in the Twill Woven graft). The Gelseal^{R} prosthesis was also manufactured by Vascutek and coated with gelatin.

The Hemashield^{R} prostheses were coated with collagen rather than gelatin. The woven variety has an alternating 1/1 plain and 6/4 satin weave construction (Figure 2c), also consists of flat and textured multifilament yarns and has a fabric count of (38 warp plain + 30 warp floats) x 39 weft yarns per square centimetre of fabric. Its fabric thickness and yarn nominal linear density are about the same as those of the sealed Twill Woven prosthesis. The knitted variety, on the other hand, is a 2-bar reverse locknit structure with tricot laps (Figure 2d), having a stitch density of 22 wales x 32 courses cm^{-2}. The knitted Hemashield^{R} prosthesis is thicker than the sealed Twill, has a slightly higher mass per unit area and consists of both flat and textured multifilament yarns of lower nominal linear density than those found in the sealed Twill Woven prosthesis.

3.3.1.3. Physical properties:

The physical properties of the prostheses are listed in Table 4. The bursting strength obtained for the unsealed Twill Woven prosthesis (280 Newtons) was slightly lower than that obtained for the sealed Twill

(305 Newtons). The Gelseal^{R}, Hemashield^{R} knitted and Hemashield^{R} woven prostheses had bursting strengths of 279, 111 and 369 Newtons respectively. The difference in the water permeability values (80 ml min^{-1} cm^{-2} for the unsealed Twill and 0 ml min^{-1} cm^{-2} for the sealed Twill) shows the effect of the coating on the prosthesis. The coated control prostheses had water permeability values ranging from 0 to about 2 ml min^{-1} cm^{-2} and their dilation values at 120 mmHg fell within the range 0.3 - 0.4%. The suture retention strength measured at 90° (i.e perpendicular) to the longitudinal axis of the Twill Woven prosthesis was higher than the values obtained at 0 or 45°. This trend was also observed with the sealed Twill Woven prosthesis. The Gelseal^{R}, however, had the lowest suture retention strength at 90° while the Hemashield^{R} woven variety showed the highest suture retention strength at 0° (i.e. parallel) to the longitudinal axis and the lowest strength at 45° to the longitudinal axis. The results of the physical tests are presented graphically in Figures 3 - 6.

3.3.1.4. Chemical properties

3.3.1.4. FTIR-ATR:

Figure 7a shows the FTIR-ATR spectra obtained for the sealed and unsealed prostheses studied. The sealed Twill Woven prosthesis had absorption bands around 3312, 2919, 2864, 1644, 1549, 1452, 1040 and 921 cm^{-1} which were absent in the spectrum of the unsealed control and were, therefore, attributed to the gelatin (Figure 7b). The observed peaks and their assignments are listed in Table 5. The peak at 3312 cm^{-1} was assigned to the N-H stretching vibration of gelatin. The amide I band was observed at 1644 cm^{-1} while the amide II band was seen at 1549 cm^{-1} and the amide III band at 1452 cm^{-1}. The spectra of the collagen-coated prostheses were only slightly different from those of the gelatin-coated grafts. Only small differences in the peak positions were observed between the two sets of

spectra (Figures 7b and c).

3.3.1.5. Level of extractables:

The total level of extractables (28.7) for the sealed Twill Woven prosthesis was much higher than that measured for the unsealed control (1.5) [Table 6] and is about the same as the weight of gelatin on the sealed prosthesis. The highest level (10.6%) was obtained with 0.1N HCl, followed by 7.2% in methanol. Extraction with 1,1,1-trichloroethane yielded 5.5% extractables while hexane yielded only 3.2% extractables. The other control grafts also showed high levels of extractable materials with the Gelseal^{R} having the highest value (46.1%) which also agrees with the weight of coating on the prosthesis. The collagen coated Hemashield^{R} prostheses had extractable levels which were lower than the weights of coating on the prostheses, an indication that all of the coating was not extracted by the series of solvents used.

3.3.1.6. Weight of coating:

Table 7 shows the weight of coating on each of the prosthesis examined. The average weight of gelatin on the sealed Twill Woven prosthesis was 287 ± 15 mg compared to 492 ± 11 mg of coating/g of prosthesis on the Gelseal^{R} and 348 ± 20 mg of collagen/g of prosthesis on the Hemashield^{R} knitted prosthesis. The Hemashield^{R} woven prosthesis had 311 ± 9 mg of collagen/g of prosthesis. These results are presented diagrammatically in Figure 8.

3.3.2. <u>In vivo investigation:</u>

3.3.2.1. Implantation, follow up and haematological analyses:

Eight dogs were required to complete the implantation schedule. In spite of the coating on the sealed Twill Woven graft, it exhibited

excellent handling characteristics during operation. Suturing was very easy and for each implantation, both anastomoses were completed within 28.4 ± 2.1 minutes.

Angiographies performed prior to the sacrifice showed that the sealed Twill Woven graft explanted at 3 months was patent and slightly bent in the abdominal region. The graft explanted at 6 months was also slightly bent in four different regions of the prosthesis. The haematological profile of each dog taken before the operation and at sacrifice showed a decrease in platelet counts at the time of sacrifice for all the dogs which correlated with an increase in the coagulation time (Hemochron). On the other hand, an increase in leukocyte count, which corresponded to an acute response to a foreign material, was observed at 24 and 48 hours after implantation. The leukocyte counts for implantation times ranging from 1 week to 6 months were, however, similar to those observed before the operation. In addition, the thrombogenic index of the implanted sealed Twill Woven grafts remained similar to that of the unsealed control.

3.3.2.2. Macroscopic observations:

The macroscopic and healing characteristics of the sealed Twill Woven grafts are presented in Table 8. Grafts implanted for 4 hours to one week had luminal surfaces covered by thick thrombotic matrices limited to the crimps of the grafts. The thrombotic matrix decreased with time as reorganization took place and a collagenous external capsule was present at two weeks in the abdominal region. Thereafter, the grafts were completely covered by granulation tissue. The grafts explanted from two weeks to six months after implantation were slightly bent in the distal region due to the thoraco-abdominal bypass model which uses a termino-lateral anastomosis distally.

3.3.2.3. Histological and SEM studies:

Fibrin and thrombi were present on the luminal surface of the sealed Twill Woven grafts explanted at 4, 24, 48 hours and 1 week respectively. In addition, a moderate acute phase of inflammation with numerous PMNs (Figure 9) was observed in contact with the gelatin. At two weeks, a collagenous internal capsule was in development at the proximal anastomosis. The gelatin was completely bioeroded and the inflammatory reaction was mild as few PMNs and lymphocytes were present. The mid-portion of the graft was covered by thrombi and surrounded externally by a loose collagenous tissue. The graft explanted at one month revealed a thin collagenous internal capsule which filled the crimps at the proximal anastomosis and extended further towards the medial region of the graft compared to what was observed with the preclotted graft. Endothelial-like cells were observed on the graft surface (Figure 10) and the presence of few macrophages indicated a chronic and mild inflammatory reaction. A thick, collagenous capsule had formed externally and the mid-portion of the graft was partially reorganized by collagen. Some endothelial-like cells were also present on the luminal surface. The inflammatory reaction was moderate. Distally, a thin collagenous internal capsule was observed extending a few centimetres from the anastomosis. At three months, the internal capsule was covered proximally by a thin thrombotic film and became thicker and fibrous in the mid-portion of the graft. The inflammatory reaction was discrete. At six months, the collagenous internal capsule was thicker and acellular on the proximal segment of the graft. Endothelial-like cells were also observed. Distally, the internal capsule was thin, cellular and endothelialized (Figure 11).

3.3.2.4. Fibrin and platelet uptake:

Table 9 shows fibrin and platelet uptake levels on the luminal

surfaces of the sealed Twill Woven grafts. These were calculated as percentages of labelled fibrin and platelets in CPM present on the graft surface after 30 minutes based on the total quantity of labelled fibrin and platelets injected. Fibrin accumulation on the graft surface was of the order of 10^{-2} and the percentage of platelets fell within the range 0.035 - 0.62%. The proximal and medial regions showed higher levels of fibrin and platelet accumulation than the distal region. These results show the low thrombogenicity of the sealed Twill Woven grafts.

3.3.2.5. Prostaglandin secretion:

The luminal surface function of the sealed Twill Woven grafts was evaluated by means of the average PGI_2/TXA_2 ratio determined on the proximal, medial and distal regions for each period of implantation. Grafts explanted at 4, 24, 48 hours and 1 week had PGI_2/TXA_2 ratios below 1.0. At 2 weeks, the ratio had reached 1.0 and there was simultaneous endothelialization of the graft. For the graft explanted at 6 months, the mean ratio PGI_2/TXA_2 was 13.1 ± 10.9. The control thoracic aorta, on the other hand, had a value of 41.7 ± 31.1 ($n = 16$).

3.3.3. Cleaned explanted grafts:

3.3.3.1. Textile/Yarn properties:

The data obtained for the textile and yarn properties of the cleaned, explanted sealed Twill Woven grafts are presented in Table 10. Measurements were taken only on grafts explanted after 3 months since we felt that the greatest changes would be observed with grafts implanted for long periods. The filament diameter and the fabric count remained relatively constant over the six month implantation period.

3.3.3.2. Physical properties:

With the limited amount of explanted materials available, only bursting strength tests could be performed on grafts explanted after one week of implantation. The results are presented in Table 11. The graft explanted after one week had an average bursting strength of 356 ± 6.3 N. This average was obtained from five measurements and is higher than the bursting strength of the virgin (305 ± 9 N) or the cleaned control (329 N). After 2 weeks of implantation, the bursting strength decreased to 328 N (2 measurements) and then 272 ± 34.2 N for 4 weeks (the lowest value obtained). The graft implanted for 3 months had a bursting strength of 280 ± 16.3 N and the 6 month graft had a bursting strength of 305 N. This latter value was obtained from just one measurement.

3.3.3.3. Chemical properties:

Typical FTIR-ATR spectra obtained for the cleaned, explanted grafts are presented in Figure 12. The spectra were identical to that of the unsealed Twill Woven prosthesis. All of the infrared features due to the gelatin had disappeared and only features due to poly(ethylene terephthalate) {PET} polyester were observed.

3.3.3.4. DSC Data for explanted materials:

The DSC data for the explanted materials are presented in Table 12. It was possible to measure Tg, Tm, heat of fusion and crystallinity indices for the explanted materials because the gelatin coating had been completely removed. The crystallinity index was constant at 0.40 for all of the explanted grafts, an indication that the six month period of implantation had no effect on the microstructure of the polyester. In addition, very little variation in average peak temperatures for the explanted samples as a function of implantation time was noted.

3.4. DISCUSSION:

The poor healing characteristic of woven prostheses is closely associated with their very low porosities[4], an important feature in controlling blood loss at implantation but an obvious limitation in graft healing. Highly porous knitted grafts, on the other hand, may have high healing capacities but are usually associated with bleeding. Since the introduction of synthetic grafts, intermittent attempts[5-7] have been made to temporarily seal knitted grafts. Such grafts are known as compound prostheses or more specifically, as coated textiles. Graft sealants are usually resorbable by the body. Early attempts at producing functional coated textile prostheses were not very successful for reasons which include the following (1) interference of the sealant with the surgical handling properties of the graft (2) unpredictable porosity control resulting from cracking and peeling of the coating (3) interference with graft healing and acceleration of graft occlusion (4) unpredictable sealant resorption rate and (5) risk of embolism.

The properties of the sealed Twill Woven prosthesis will be discussed along these lines. The sealed Twill Woven graft is a textile prosthesis, coated with approximately 287 mg of gelatin per gram of prosthesis. It was only slightly less flexible than the unsealed variety. Nevertheless, it had excellent handling and suturing characteristics. For each implantation, both anastomoses were completed within 28.4 ± 2.1 minutes compared to 25.2 ± 2.2 minutes for the unsealed variety. The gelatin coating effectively reduced the water permeability of the Twill Woven prosthesis to 0 ml min^{-1} cm^{-2} so that preclotting was not required and no blood loss occurred at implantation. There was also no case of infection during the post-implantation period.

Healing characteristics, sealant resorption and embolism: Grafts implanted for from 4 hours to 1 week exhibited a moderate acute phase of

inflammation (numerous PMNs were found in contact with the gelatin). At 2 weeks, the inflammatory reaction was mild, the gelatin was completely bioeroded and a collagenous internal capsule was in development at the proximal anastomosis. Endothelial-like cells were present on grafts implanted for one month or longer. All in all, the graft healed satisfactorily and there was no observed increase in the thrombogenic index of the sealed Twill over the unsealed control.

The rationale for the compound graft concept is to produce a prosthetic wall with a low porosity which controls blood loss at implantation, but has a significantly high healing capacity in the long term following resorption of the absorbable component[8]. Several studies[9-17] indicate that coated grafts can prevent blood loss at implantation, reduce the risk of infection during the post implantation period and heal satisfactorily depending on the nature and method of preparation of the sealant. In addition, there is some evidence[9] to indicate that graft sealing with a substance that undergoes removal at a moderate rate is efficacious and safe. The gelatin coated Twill Woven prosthesis performed satisfactorily in the animal model used in our study and might also perform satisfactorily in human beings. The results will depend to a large extent on the status and progression of the arterial disease as well as the attention paid in applying the appropriate surgical techniques[18].

Some of the limitations of this study will be discussed below. Only gelatin- and collagen-sealed polyester vascular prostheses were analyzed <u>in vitro</u>. The type of sealant, method of cross-linking and softening of the vascular prostheses had been established by the different manufacturers and could not be controlled in this study. For each prosthesis, the sample was limited to one batch. The number of tests that could be performed with the explanted samples was limited by the amount of material available. The <u>in vivo</u> study was done only on the Twill Woven

varieties so that direct comparisons with the sealed controls was not possible.

3.5. CONCLUSION:

The in vivo biofunctionality and biostability of the sealed Twill Woven prosthesis were evaluated by implanting segments of the prosthesis as thoraco-abdominal by-passes in adult mongrel dogs for periods ranging from 4 hours to 6 months. The in vitro characteristics of the prosthesis were also compared to those of the unsealed Twill Woven prototype and other collagen or gelatin sealed prostheses. The in vitro study showed that the sealed Twill Woven Prosthesis performed as well as any of the sealed control prostheses. A water permeability of zero was obtained for the sealed Twill Woven prototype so that the prosthesis did not require preclotting prior to implantation and no blood loss occurred at implantation. In addition, no sign of infection was observed during the post implantation period. The graft healed satisfactorily and no adverse biological response occurred as a result of the gelatin coating. Analyses of the explanted grafts did not reveal any significant changes either in the microstructure of the polyester, or the fabric count and the bursting strength of the prosthesis which led us to conclude that the prosthesis maintained its biostability in vivo.

3.6. REFERENCES:

1. Guidoin R., King M., Marois M., Martin L., Marceau D., Hood R., & Maini R. New polyester arterial prostheses from Great Britain: an in vitro and an in vivo evaluation. Ann. Biomed. Eng., 1986, 14: 351-367.

2. Guidoin R., Gosselin C., Martin L., Marois M., Laroche G., King M., Gunasekera K., Domurado D., Sigot-Luizard M.F. & Blais P. Polyester prostheses as substitutes in the thoracic aorta of dogs. I. Evaluation of commercial prostheses. J. Biomed. Mater. Res., 1983, 17: 1049-1077.

3. Guidoin R., King M., Therrien M., Douville Y., Debille E., Boyer D., Simoneau S., & Tremblay L. Woven velour polyester arterial grafts with polypropylene wrap: a cosmetic change or an improved design. In High Performance Biomaterials: a comprehensive guide to medical and pharmaceutical applications. M. Szycher (ed.), Technomic Publishing Co. Inc., Lancaster, Pennsylvania, U.S.A., 1991, pp. 449-474.

4. Wesolowski S.A., Fries C.C., Karlson K.E., DeBakey M., & Sawyer P.N. Porosity: primary determinant of ultimate fate of synthetic vascular grafts. Surgery, 1961, 50: 91-96.

5. Humphries A.W., Hawk W.A., & Cuthbertson A.M. Arterial prosthesis of collagen-impregnated Dacron tulle. Surgery, 1961, 50: 947-954.

6. Bascom J.U. Gelatin sealing to prevent blood loss from knitted arterial grafts. Surgery, 1961, 50: 504-512.

7. Jordan G.L., Stump M.M., Allen J., DeBakey M.E., & Halpert B. Gelatin impregnated prosthesis implanted into porcine thoracic aorta. Surgery. 1963, 53: 45-49.

8. Wesolow, A. Biologic behavior of tissue and prosthetic grafts in Vascular Surgery: Principles and Techniques. H. Haimovici (ed). Appleton-Century-Crofts, Norwalk. 1984, pp 93-118.

9. Jonas, R.A., Ziemer, G., Schoen, F.J., Lewis, B., & Castaneda, A.R. A new sealant for knitted Dacron® prosthesis: minimally crosslinked gelatin. J. Vasc. Surg., 1988, 7: 414-419.

10. Guidoin R., Merhi Y., Sigot M.F., Blais P., Rao T.J., Marceau D. & Paynter R. Collagen coated polyester arterial prostheses: an evaluation. Transplantation and Implantation Today, 1988, 5: 21-25.

11. Haverich, A., Oelert, H., Maatz, W., & Borst, H.G. Histopathologic evaluation of woven and knitted Dacron® grafts for right ventricular conduits: a comparative experimental study. Ann. Thoracic Surg., 1984, 37: 404-411.

12. Stratton J.W., & Hall R.V. Pseudointimal embolism from a woven Dacron® graft. Surgery, 1979, 86: 772-773.

13. Jonas R.A., Schoen F.J., Levy R.J., & Castaneda R.A. Biological sealants and knitted Dacron®: porosity and histological comparisons of vascular graft materials with and without collagen and fibrin glue pretreatments. Ann. Thoracic Surg., 1986, 41, 657-663.

14. Lundsgaard-Hansen P., & Tschirren B. Clinical experience with 12,000 units of modified fluid gelatin. Proceedings of the Joint WHO/IABS Symposium on Standardization of Albumin, Plasma Substitutes and Plasmopheresis. 1981, 48: 251-256.

15. McGee G.S., Schuman T.A., Atkinson J.B., Weaver F.A., & Edwards W.H. Experimental evaluation of a new albumin-impregnated knitted Dacron® prosthesis. Am. Surgeon. 1987, 53: 695-701.

16. *Reigel M.M., Hollier L.H., Pairolero P.C., & Hallet J.W. Early experience with a new collagen-impregnated aortic graft. Am. Surgeon. 1988, 54: 134-136.*

17. *Sottiurai V.S., Sue S.L., Rau D.J., & Tran A.B. Comparative analysis of pseudointima biogenesis in Gelseal coated Dacron® knitted graft versus crimped and non crimped graft. J. Cardiovasc. Surg., 1989, 30: 902-909.*

18. *Haimovici H. History of vascular surgery in Vascular Surgery: Principles and Techniques, H. Haimovici (ed)., Appleton-Century-Crofts, Norwalk, 1984, pp 3-18.*

3.7. TABLES:

TABLE 1: GRAFTS SELECTED FOR STUDY

Prostheses	Manufacturer	Fabric type	Coating product	Prosthesis diameter
Twill Woven	Vascutek, UK	1/1 plain + 3/1/1/1 float		8mm
Sealed Twill	Vascutek, UK	1/1 plain + 3/1/1/1 float	gelatin	8mm
Gelseal®	Vascutek, UK	2-bar reverse locknit with open cord laps	gelatin	20mm
Hema-shield® knitted	Meadox, USA	2-bar reverse locknit with tricot laps	collagen	8mm
Hema-shield® woven	Meadox, USA	1/1 plain + 6/4 satin double velour	collagen	8mm

TABLE 2: TEXTILE PROPERTIES FOR THE PROSTHESES STUDIED.

Prostheses	Ends/Wales (cm^{-1})	Picks/Courses (cm^{-1})	Thickness (mm)	Mass/Unit Area (g/m^2)
Twill Woven	42p 22f	48	0.35	172
Sealed Twill	42p 22f	48	0.40	265
Gelseal®	12	16	0.65	658
Hemashield® knitted	22	32	0.55	315
Hemashield® woven	38p,30f	39	0.42	276

TABLE 3: YARN PROPERTIES OF THE PROSTHESES INCLUDED IN THE STUDY.

Prostheses	Yarn type	Yarn nominal linear density (decitex)	Approximate filament count	Filament diameter (μm)	Delusterant level
Twill Woven	flat mf	102	54 warp p	13.2±1.3	semi dull
		102	54 warp f	13.2±1.3	semi dull
		118	54 weft	14.2±1.7	semi dull
Sealed Twill	flat mf	102	54 warp p	13.2±1.3	semi dull
		102	54 warp f	13.2±1.3	semi dull
		118	54 weft	14.2±1.7	semi dull
Gelseal^{R}	textured mf	186	105 inside	12.8±0.8	semi dull
		91	54 outside	12.5±1.6	semi dull
Hemashield^{R} knit	flat and textured mf	46	27	12.6±1.4	semi dull
Hemashield^{R} woven	flat and textured mf	83	54 warp p	11.9±0.8	semi dull
		103	54 warp f	13.3±0.7	semi dull
		120	54 weft	14.3±0.8	semi dull

Note p=plain, mf=multifilament, f=floats.

TABLE 4: PHYSICAL PROPERTIES OF VIRGIN PROSTHESES ANALYSED.

Prostheses	Dilation at 120 mmHg (%)	Water permeability (ml/min/cm^2)	Suture Retention Strength (Newtons) 0°	90°	45°	Bursting Strength (Newtons)
Twill Woven	0.4	80	24.6	30.1	21.6	280+27
Sealed Twill	0.3	0	26.7	29.9	25.9	305+ 9
Gelseal^R	5.0	0	35.4	33.6	35.5	279±19
Hema-shield^R knitted	1.7	2	23.8	21.3	21.5	111± 2
Hema-shield^R woven	0.36	1	36.5	30.6	21.5	369± 8

Table 5: FTIR PEAK ASSIGNMENTS FOR VIRGIN SEALED PET PROSTHESES.

Gelatin coated Peak (cm^{-1})	Collagen coated Peak (cm^{-1})	Relative Intensity	Assignment
3312	3305	very strong	NH stretch
2919	2932	med-strong	CH stretch
2864	2878	med-strong	CH stretch
1720	1709	strong	C=O stretch
1644	1655	med-strong	amide I band
1549	1549	medium	amide II band
1452	1452	weak	amide III band
1401	1407	medium	CH_2 bending vibration
1339	1338	medium	
1235	1232	med-strong	O-C stretch of ester
1100	1108	strong	O-C stretch of ester
1040	1037	strong	
921	922	med-weak	C-C stretch of the glycol backbone in the gauche conformation
855	851	weak-med	
-	848	weak	C-H out of plane bending vibration

TABLE 6: LEVEL OF EXTRACTABLES FOR VIRGIN PROSTHESES

Prostheses	Hexane	1,1,1-trichloroethane	Methanol	Water	0.1N HCl	Total
Twill Woven	0.5	0.0	0.7	0.2	0.1	1.5
Sealed Twill	3.2	5.5	7.2	2.1	10.6	28.7
Gelseal®	1.0	2.6	40.1	1.8	0.6	46.1
Hema-shield® knit	3.6	6.5	15.4	0.4	0	25.9
Hema-shield® woven	3.7	12.5	3.1	0.1	0.1	19.5

TABLE 7: WEIGHT OF COATING ON SEALED PROSTHESES

Prostheses	Type of coating	Experimental/ Commercial	mg of coating/g of prosthesis
Sealed Twill	Gelatin	Experimental	287.38 ± 14.50
Gelseal®	Gelatin	Commercial	491.58 ± 11.19
Hema-shield® knit	Collagen	Commercial	347.92 ± 19.58
Hema-shield® woven	Collagen	Commercial	310.95 ± 9.45

TABLE 8: HEALING CHARACTERISTICS OF THE SEALED TWILL WOVEN GRAFTS IMPLANTED AS THORACO-ABDOMINAL BYPASSES IN DOGS FOR PRESCHEDULED PERIODS RANGING FROM 4 HOURS TO 6 MONTHS

Duration of Implantation	Graft Structure	External Capsule	Coating	Internal Capsule	Endothelium	Flow Surface
4 hours	straight	none	present	none	none	red thrombi
24 hours	straight	none	present	none	none	red in the crimps
48 hours	straight	none	present	none	none	red in the crimps
1 week	straight	none present	partially	none	none	red in the crimps
2 weeks	bent distally	present in the abdominal region	absent	proximal anastom-sis	yes	red
1 month	bent distally	entire graft	absent	thin and almost complete	yes	red and white
3 months	bent distally	entire graft	absent	thick and complete	yes	white with small thrombi
6 months	bent proxi-mally and distally	entire graft	absent	thick and complete	yes	white with few thrombi

TABLE 9: FIBRIN AND PLATELET UPTAKE ON THE LUMINAL SURFACE OF THE SEALED TWILL WOVEN GRAFT

Duration of Implantation	Fibrin (% x 10^2)			Platelets (%)		
	Proximal	Medial	Distal	Proximal	Medial	Distal
4 hours	0.34	0.53	0.70	0.56	0.30	0.12
24 hours	0.48	0.92	0.034	0.31	0.35	0.035
48 hours	0.38	0.24	0.051	0.31	0.35	0.037
1 week	0.44	0.20	0.098	0.31	0.36	0.05
2 weeks	0.30	0.31	0.093	0.32	0.29	0.06
1 month	0.25	0.40	0.14	0.35	0.30	0.11
3 months	0.90	1.1	-	0.62	0.49	-
6 months	0.93	0.73	0.33	0.43	0.35	0.12

TABLE 10: TEXTILE/YARN PROPERTIES FOR EXPLANTED SEALED TWILL WOVEN GRAFTS

length of implantation	filament diameter (μm)			Fabric count (cm^{-1})		
	warp p	warp f	weft	warp p	warp f	weft
0	13.2±1.3	13.2±1.3	14.2±1.7	42	22	48
3 months	13.7±2.2	13.4±1.9	13.7±2.0	42	22	48
6 months	13.8±1.9	13.6±1.6	13.5±1.4	42	22	48

TABLE 11: PHYSICAL PROPERTIES FOR EXPLANTED SEALED TWILL WOVEN GRAFTS

length of implantation	bursting strength (Newtons)	Number of measurements
0	280 ± 17	5
cleaned control	329 ± 16	4
4 hours	-	0
24 hours	-	0
48 hours	-	0
1 week	356 ± 6	5
2 weeks	328 ± 4	2
4 weeks	272 ± 34	4
3 months	280 ± 16	2
6 months	305	1

TABLE 12: DSC DATA FOR THE EXPLANTED SEALED TWILL WOVEN GRAFTS

Length of Implantation	Tg (°C)	Tm (°C)	Heat of Fusion (J/g)	Crystal-linty Index
cleaned	78.5±0.2	259.77	55.60	0.40
4 hours	77.3±0.6	256.44	57.16	0.41
24 hours	78.3±0.3	258.33	56.90	0.41
48 hours	78.8±0.1	258.53	56.64	0.40
1 week	78.1±0.3	258.87	55.52	0.40
2 weeks	76.5±0.7	258.68	55.83	0.40
4 weeks	77.8±0.3	257.69	53.08	0.38
3 months	76.1±0.8	258.30	55.88	0.40
6 months	77.9±0.4	258.66	56.51	0.40

3.8. FIGURES:

1: SEM PHOTOMICROGRAPHS OF THE VARIOUS SEALED PROSTHESES INCLUDED IN THIS STUDY. A: TWILL WOVEN PROSTHESIS. B: SEALED TWILL WOVEN PROSTHESIS. C: GELSEAL^R. D: KNITTED HEMASHIELD^R. E. WOVEN HEMASHIELD^R.

2: POINT AND LAPPING DIAGRAMS FOR THE VARIOUS PROSTHESES EVALUATED. A: TWILL WOVEN PROSTHESIS. B: GELSEAL^R. C. WOVEN HEMASHIELD^R. D: KNITTED HEMASHIELD^R.

3: DIAGRAMMATIC REPRESENTATION OF THE BURSTING STRENGTH DATA FOR THE VARIOUS PROSTHESES ANALYSED.

4: DIAGRAMMATIC REPRESENTATION OF THE WATER PERMEABILITY DATA FOR THE VARIOUS PROSTHESES ANALYSED.

5: SUTURE RETENTION STRENGTH DATA FOR THE PROSTHESES INCLUDED IN THE STUDY.

6: FIGURE SHOWING THE DILATION VALUES OF THE PROSTHESES ANALYSED.

7A: INFRA RED SPECTRA OF THE VARIOUS PROSTHESES STUDIED.

7B: INFRA RED SPECTRUM OF THE SEALED TWILL WOVEN PROSHESIS.

7C: INFRA RED SPECTRUM OF THE COLLAGEN COATED HEMASHIELD^R KNITTED PROSTHESIS.

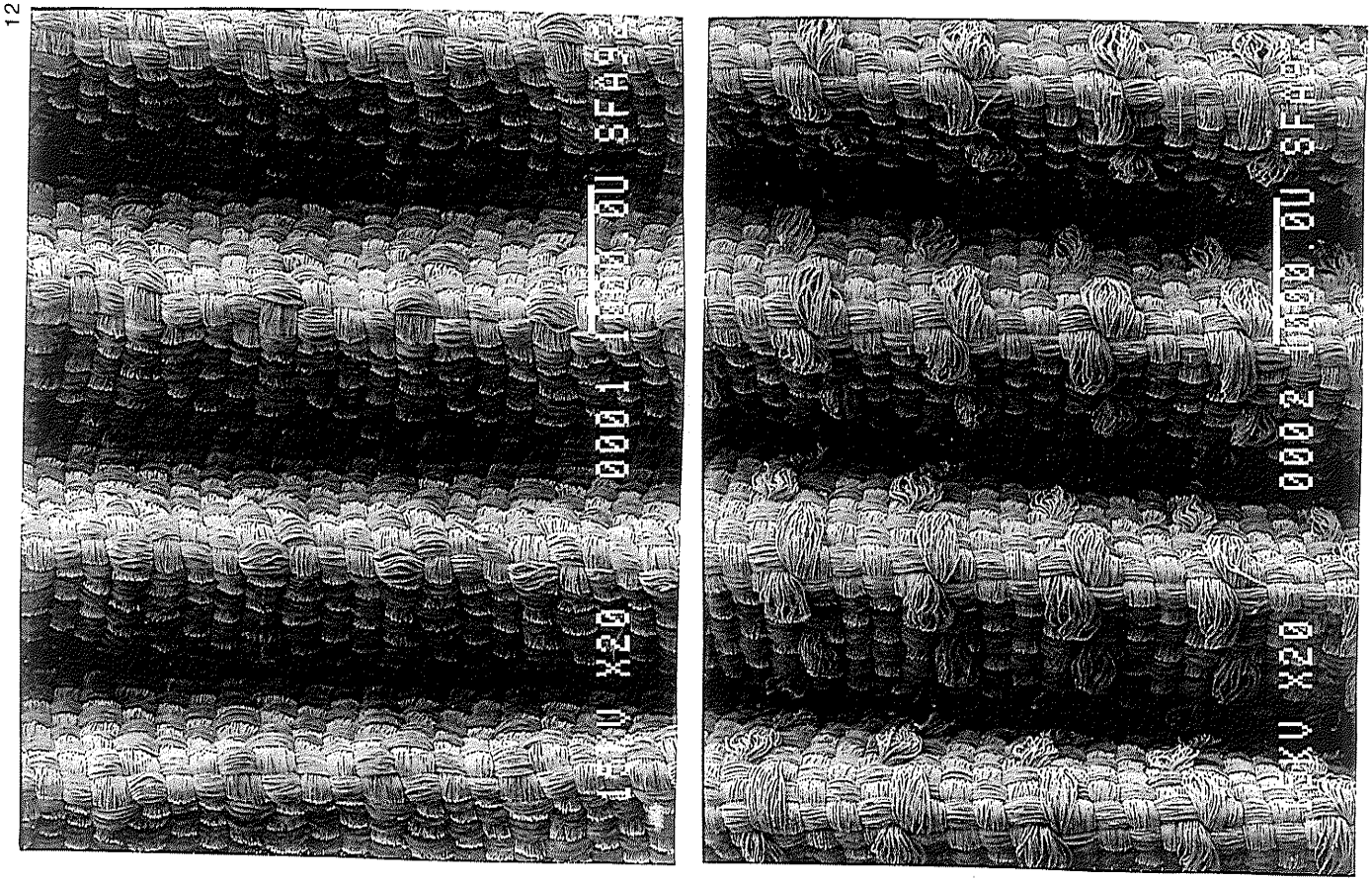
8: AMOUNT OF COATING ON THE SEALED PROSTHESES REPRESENTED AS BAR CHARTS.

9: SEALED TWILL WOVEN GRAFT EXPLANTED AFTER 48 HOURS SHOWING MODERATE INFLAMMATORY REACTION IN CONTACT WITH THE GELATIN. POLYMORPHONUCLEAR CELLS AND LYMPHOCYTES ARE EASILY OBSERVED (X2500) (HEMATOXYLIN-EOSIN).

10: SEALED TWILL WOVEN GRAFT EXPLANTED AFTER 1 MONTH SHOWING THE NEOINTIMA OF NEWLY FORMED COLLAGEN AND SOME CELLULARITY ON THE FLOW SURFACE (X1250) (MASSON TRICHROME).

11: DISTAL PORTION OF SEALED TWILL WOVEN GRAFT EXPLANTED AFTER 6 MONTHS SHOWING THIN COLLAGENOUS CAPSULE WITH CELLULARITY AND A CONTINUOUS LAYER OF CELLS COVERING THE LUMINAL SURFACE (X1500) (MASSON TRICHROME).

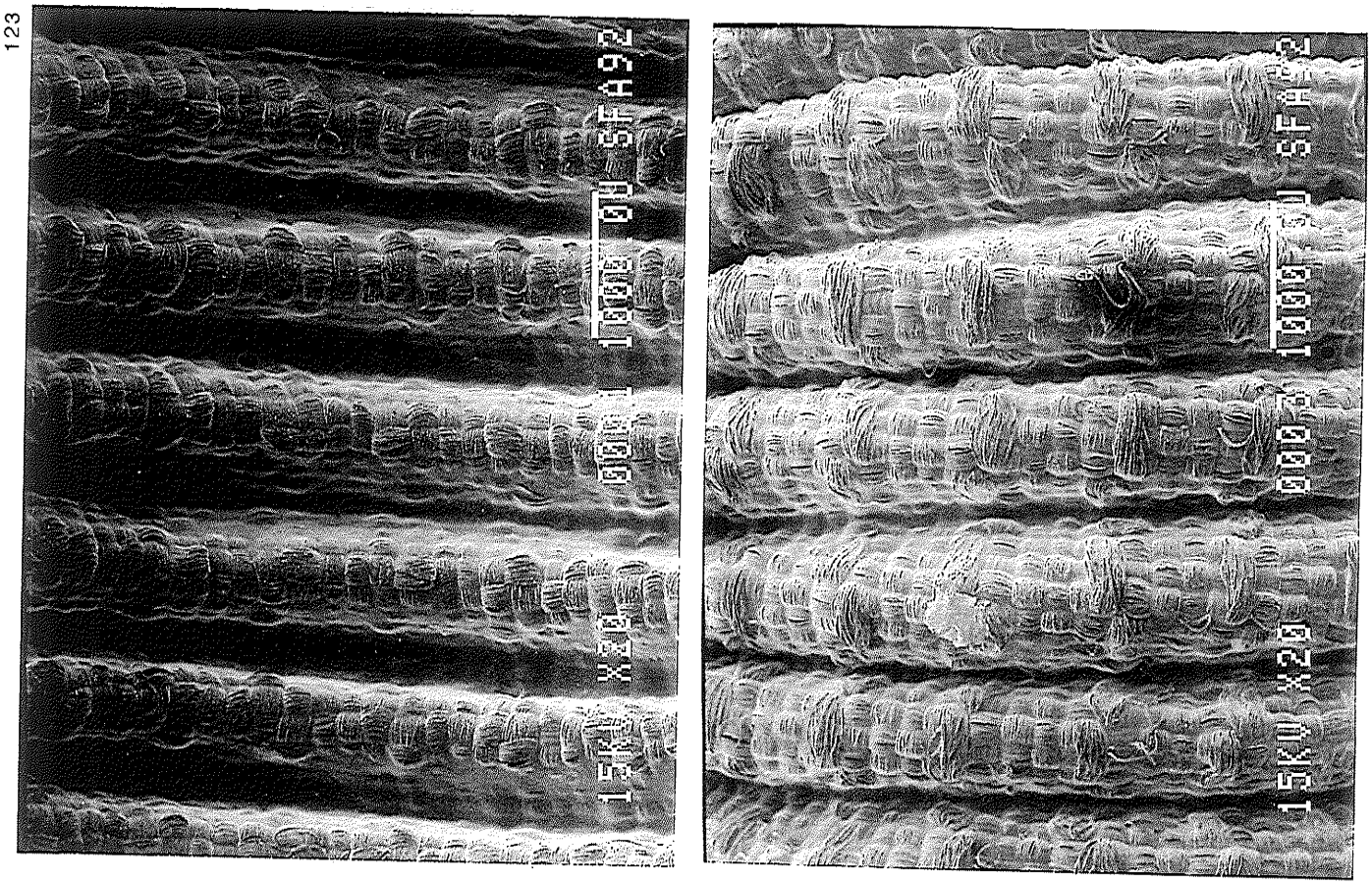
12: INFRA RED SPECTRA OF THE EXPLANTED SEALED TWILL WOVEN GRAFTS.



INTERNAL *EXTERNAL*

DIRECTION OF BLOOD FLOW

FIGURE 1A: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE TWILL WOVEN PROSTHESIS.

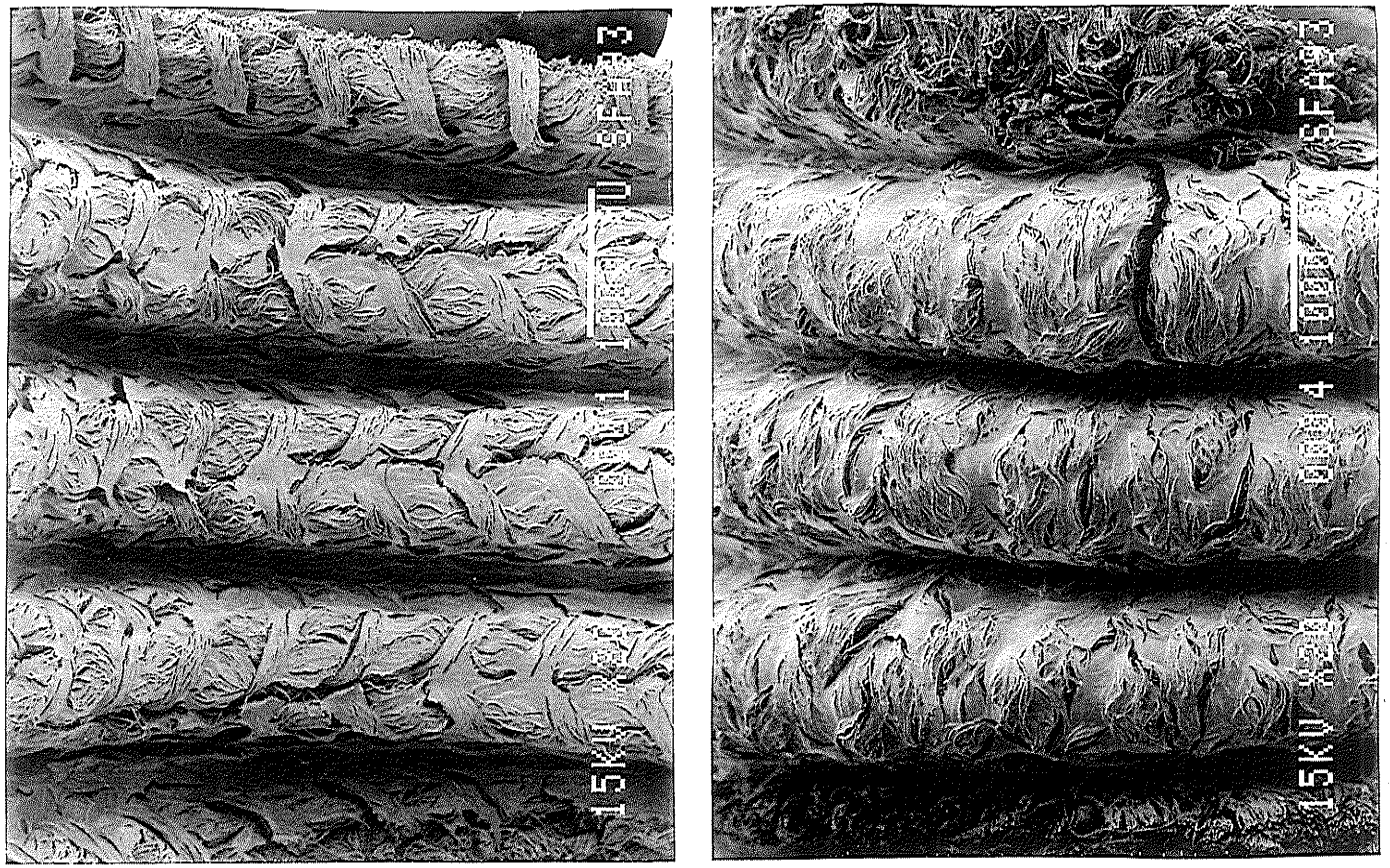


INTERNAL

EXTERNAL

DIRECTION OF BLOOD FLOW

FIGURE 1B: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE SEALED TWILL WOVEN PROSTHESIS.



INTERNAL *EXTERNAL*

DIRECTION OF BLOOD FLOW

FIGURE 1C: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE GELSEAL®.

FIGURE 1D: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE KNITTED HEMASHIELD®.

FIGURE 1E: SEM PHOTOMICROGRAPHS OF THE INTERNAL AND EXTERNAL SURFACES OF THE WOVEN HEMASHIELD®.

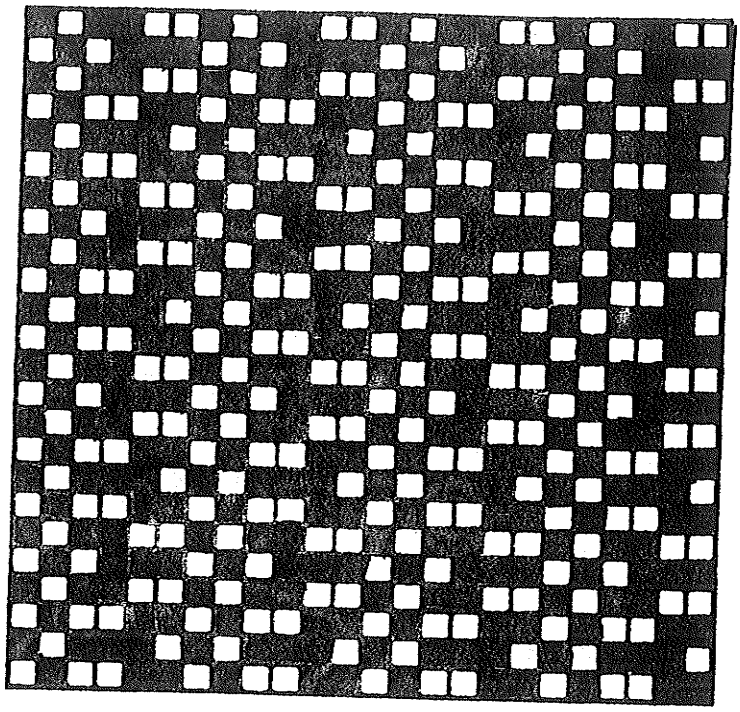


FIGURE 2A: POINT DIAGRAM OF THE TWILL WOVEN PROSTHESIS

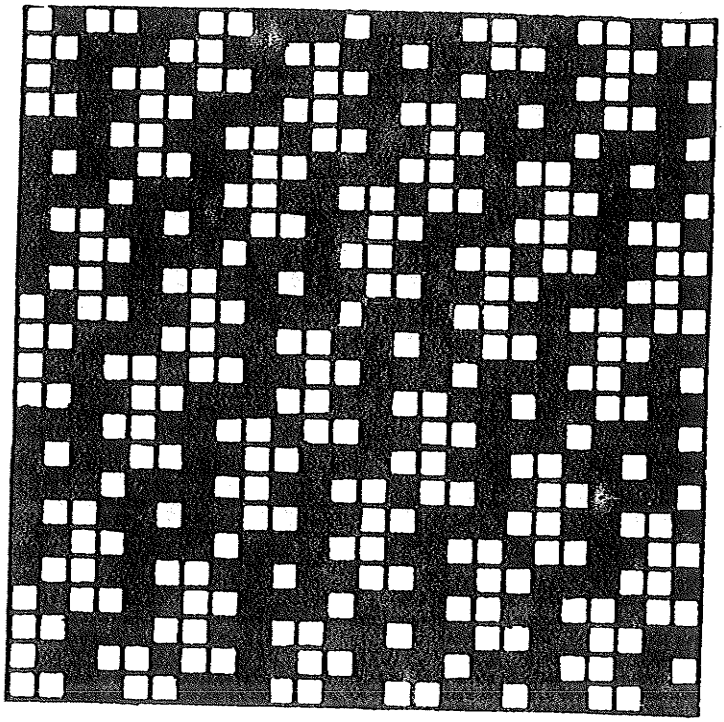
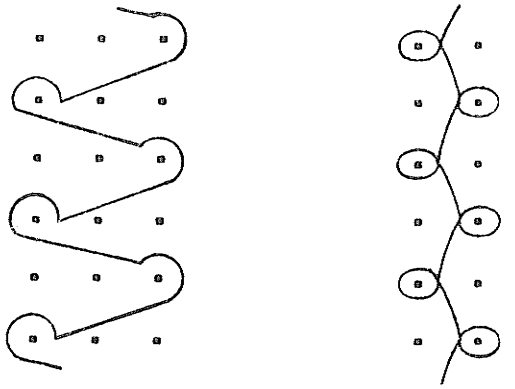


FIGURE 2C : POINT DIAGRAM OF THE MEADOX® WOVEN DOUBLE VELOUR PROSTHESIS

BACK BAR

FRONT BAR



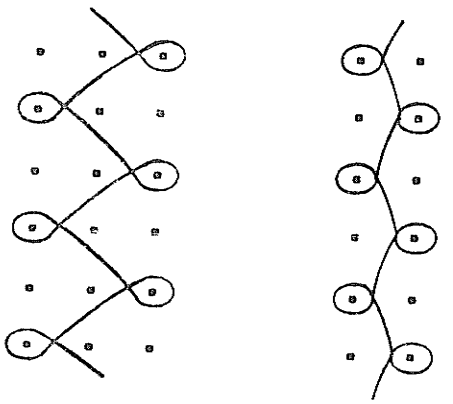
3-2\0-1

1-0\1-2

FIGURE 2B: LAPPING DIAGRAMS FOR THE GELSEAL[R] PROSTHESIS.

BACK BAR

FRONT BAR



2-3\1-0

1-0\1-2

FIGURE 2D: LAPPING DIAGRAMS FOR THE KNITTED HEMASHIELD[R] PROSTHESIS.

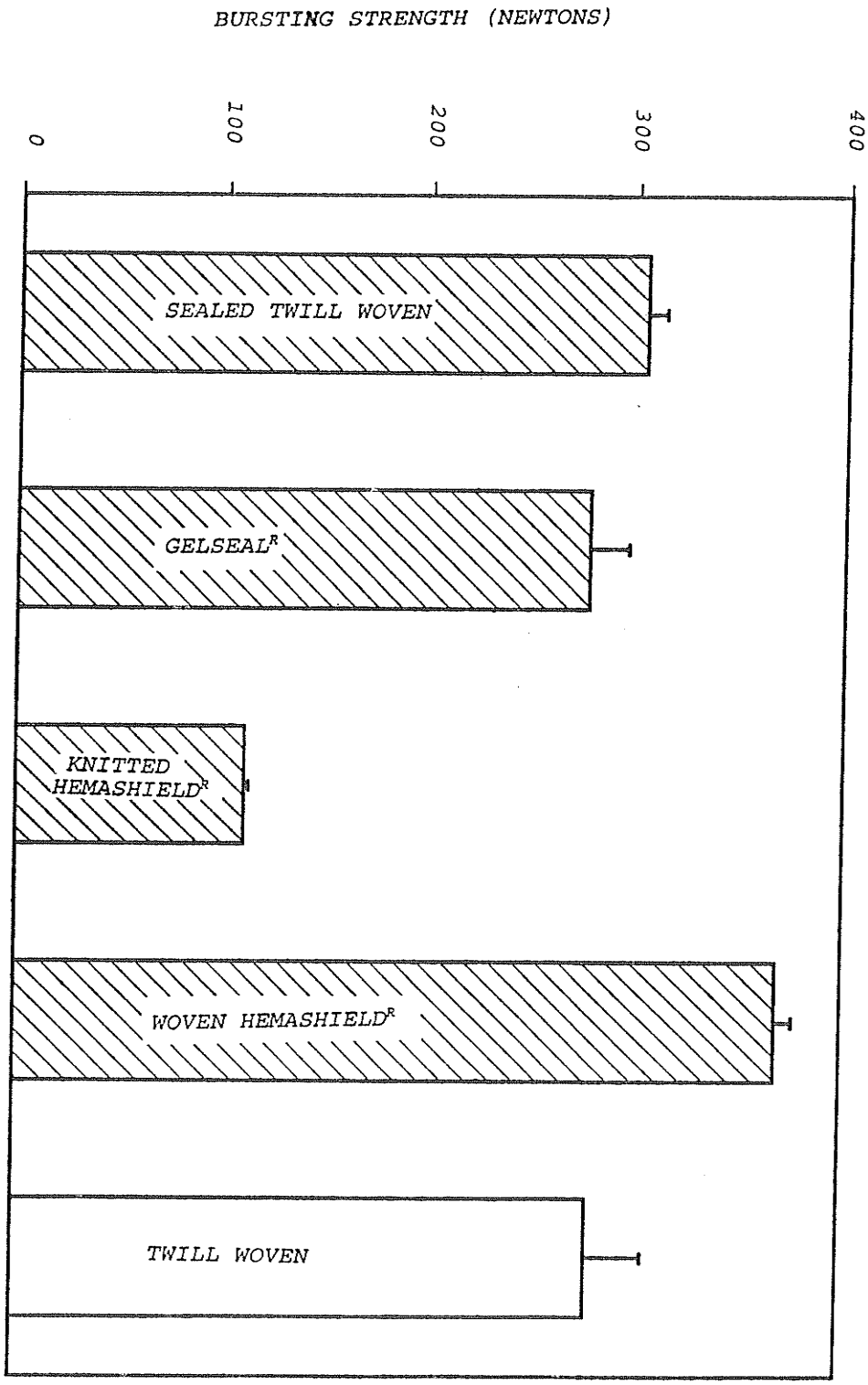


FIGURE 3: DIAGRAMMATIC REPRESENTATION OF THE BURSTING STRENGTH DATA FOR THE VARIOUS PROSTHESES ANALYSED.

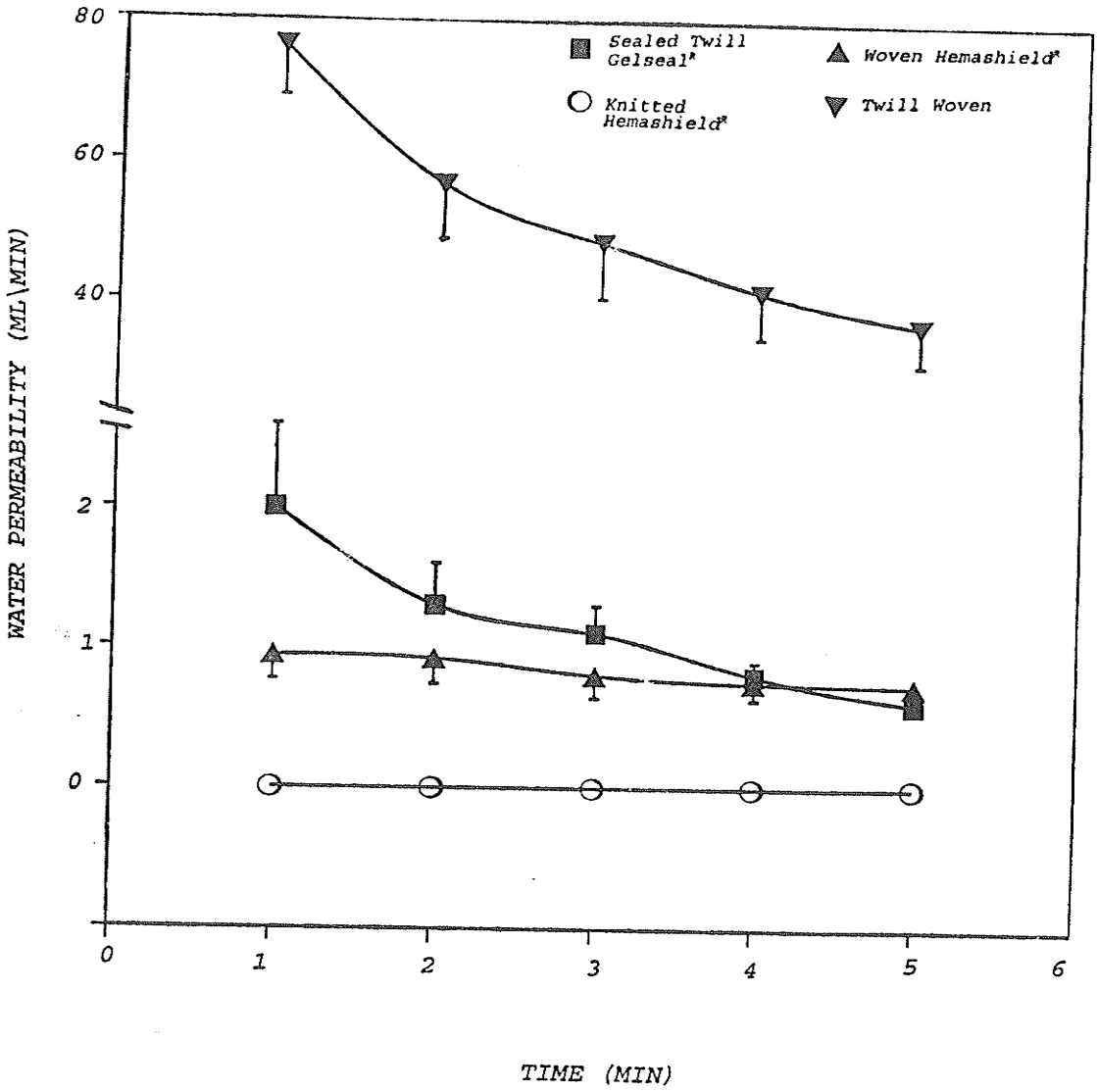


FIGURE 4: DIAGRAMMATIC REPRESENTATION OF THE WATER PERMEABILITY DATA FOR THE VARIOUS SEALED PROSTHESES STUDIED.

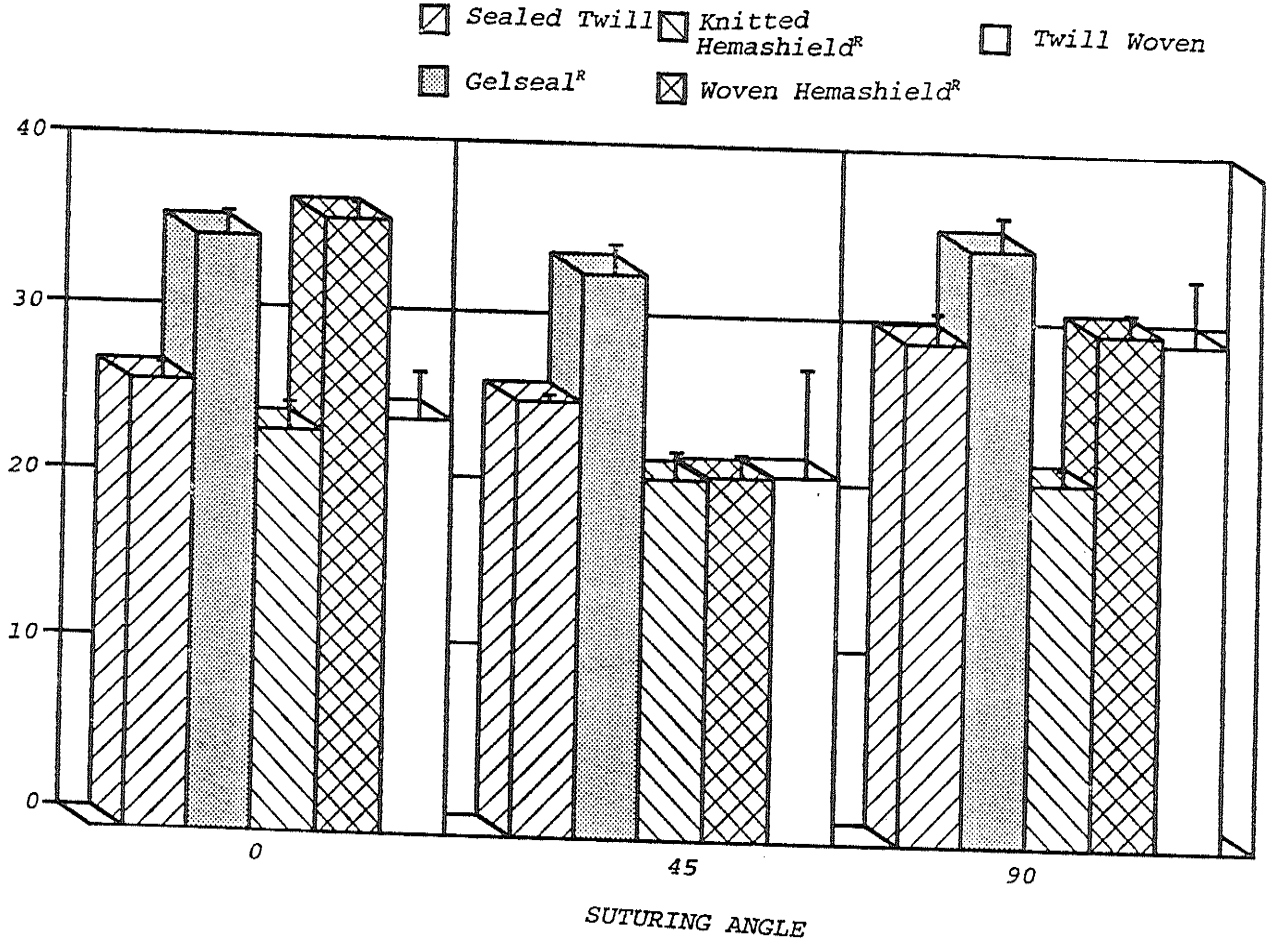


FIGURE 5: SUTURE RETENTION STRENGTH DATA FOR THE VARIOUS PROSTHESES INCLUDED IN THE STUDY.

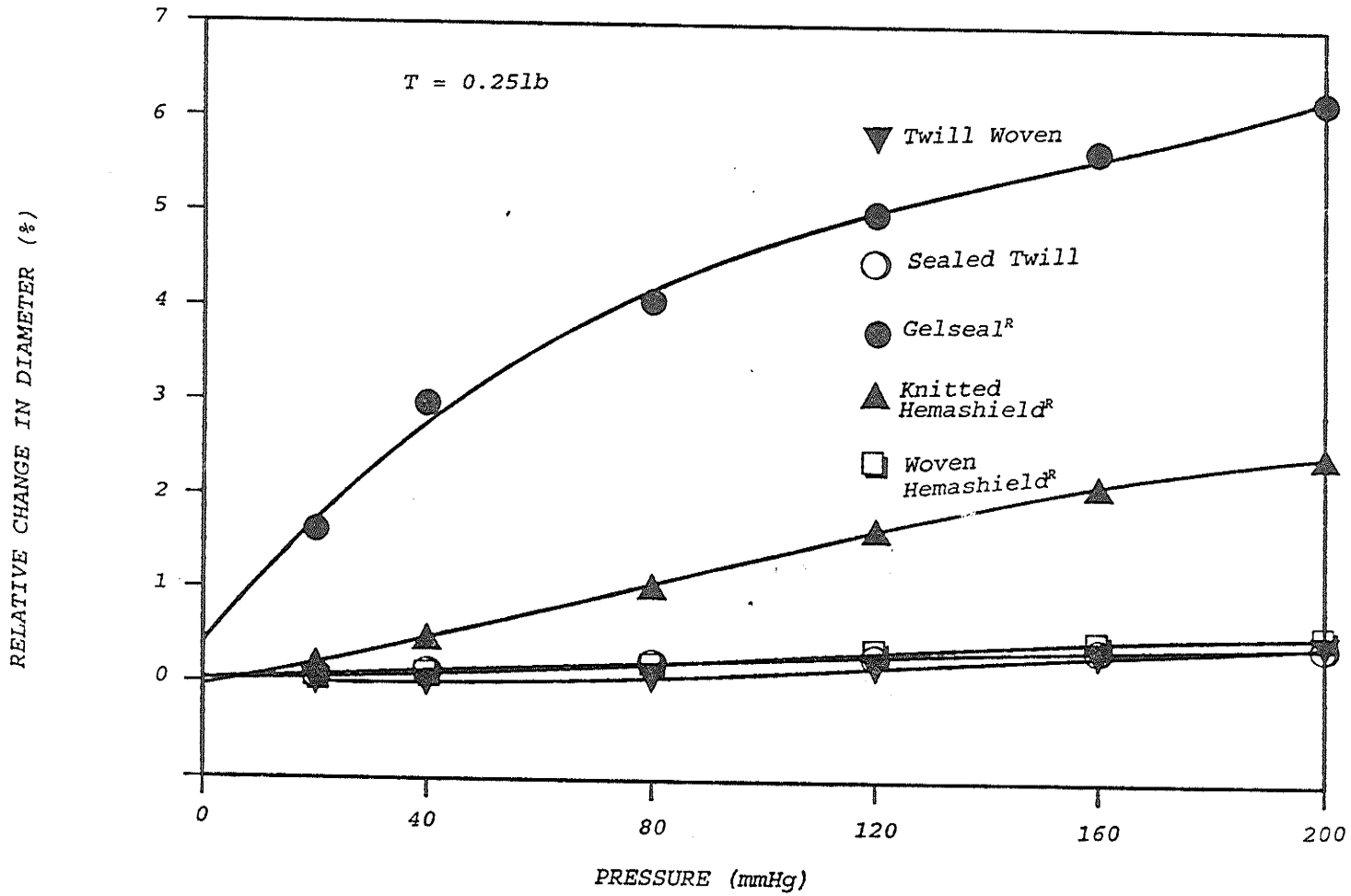


FIGURE 6: DIAGRAMMATIC REPRESENTATION OF THE DILATION DATA FOR THE PROSTHESES ANALYSED.

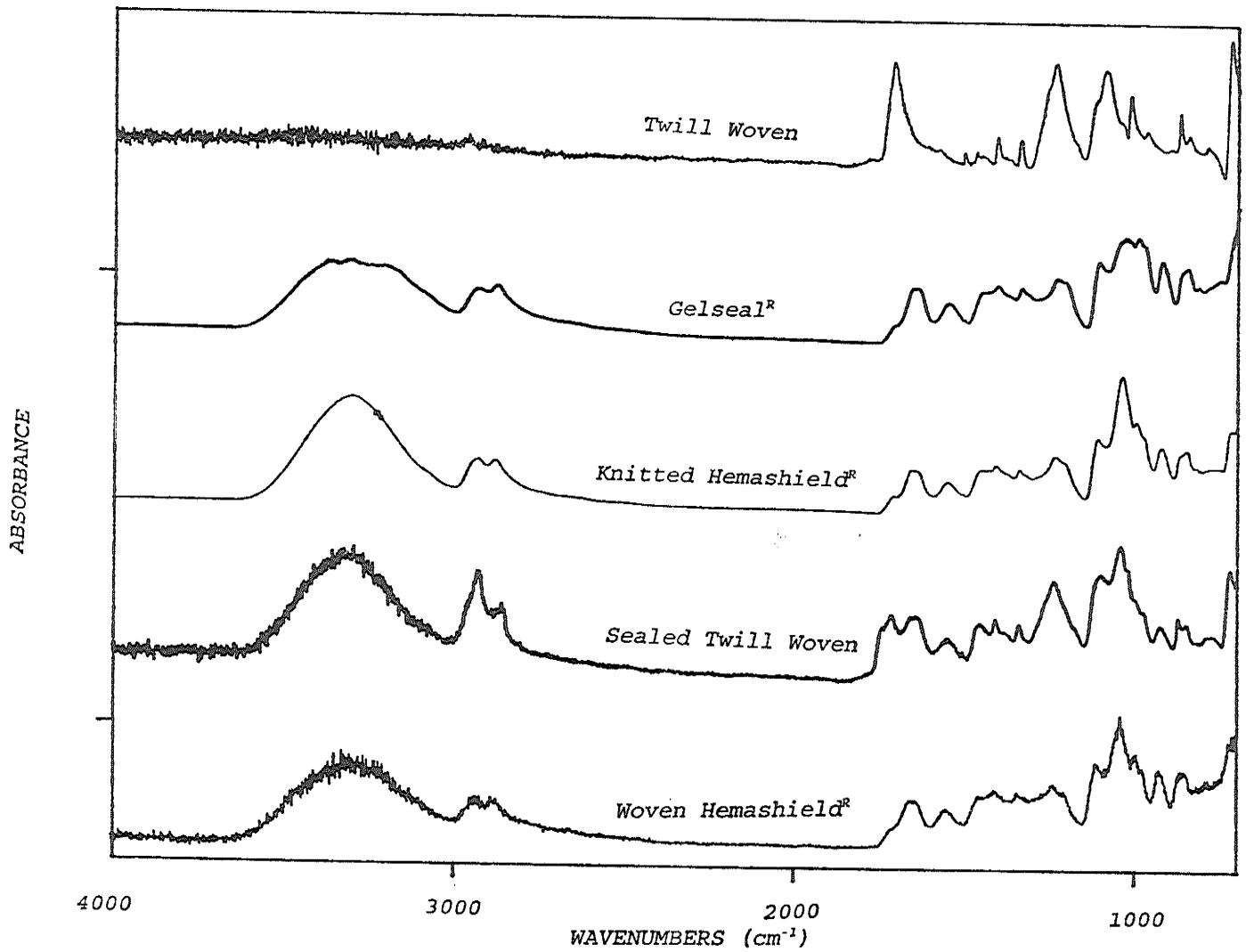


FIGURE 7A: INFRA RED SPECTRA FOR THE VARIOUS PROSTHESES STUDIED.

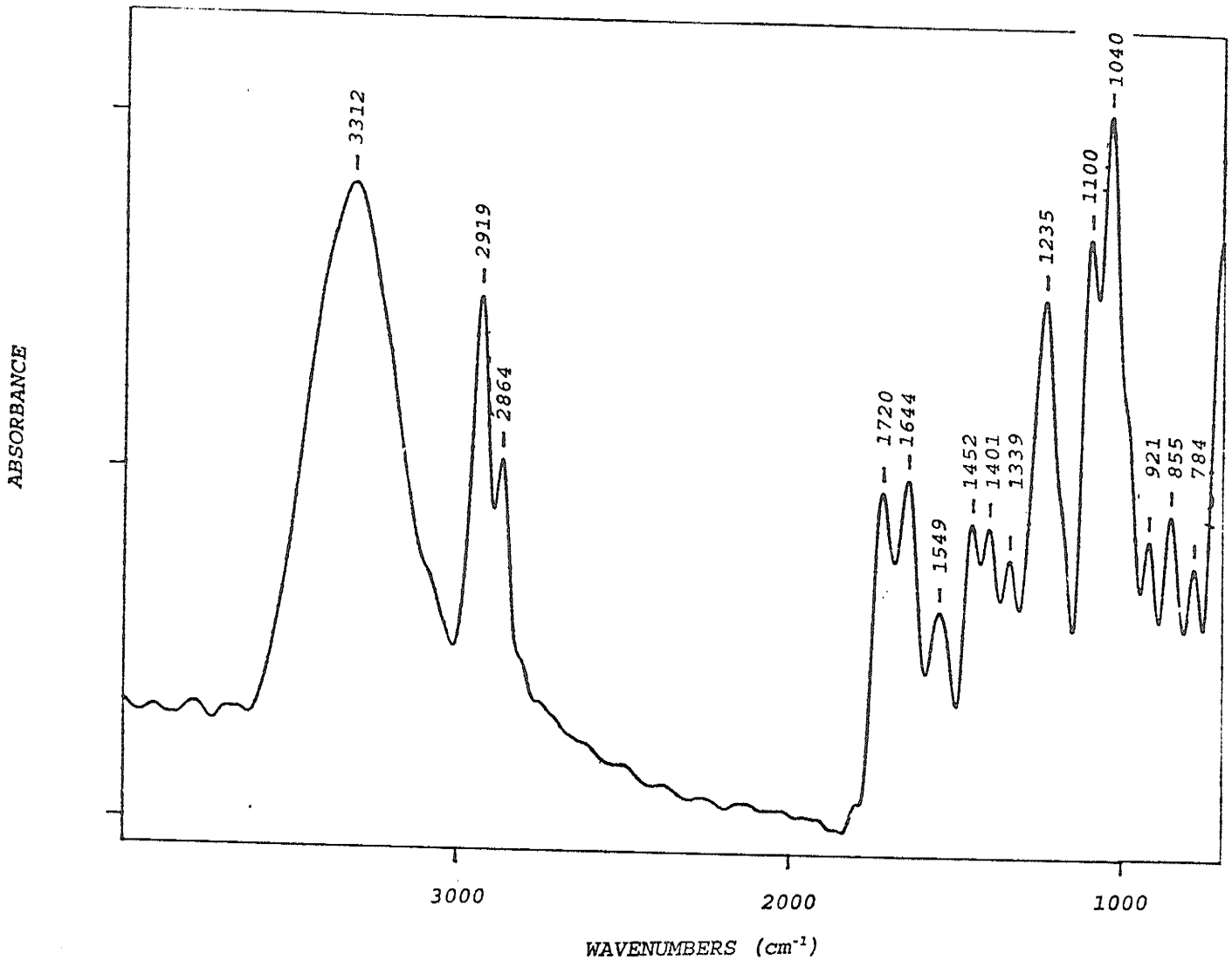


FIGURE 7B: INFRA RED SPECTRUM OF THE SEALED TWILL WOVEN PROSHESIS.

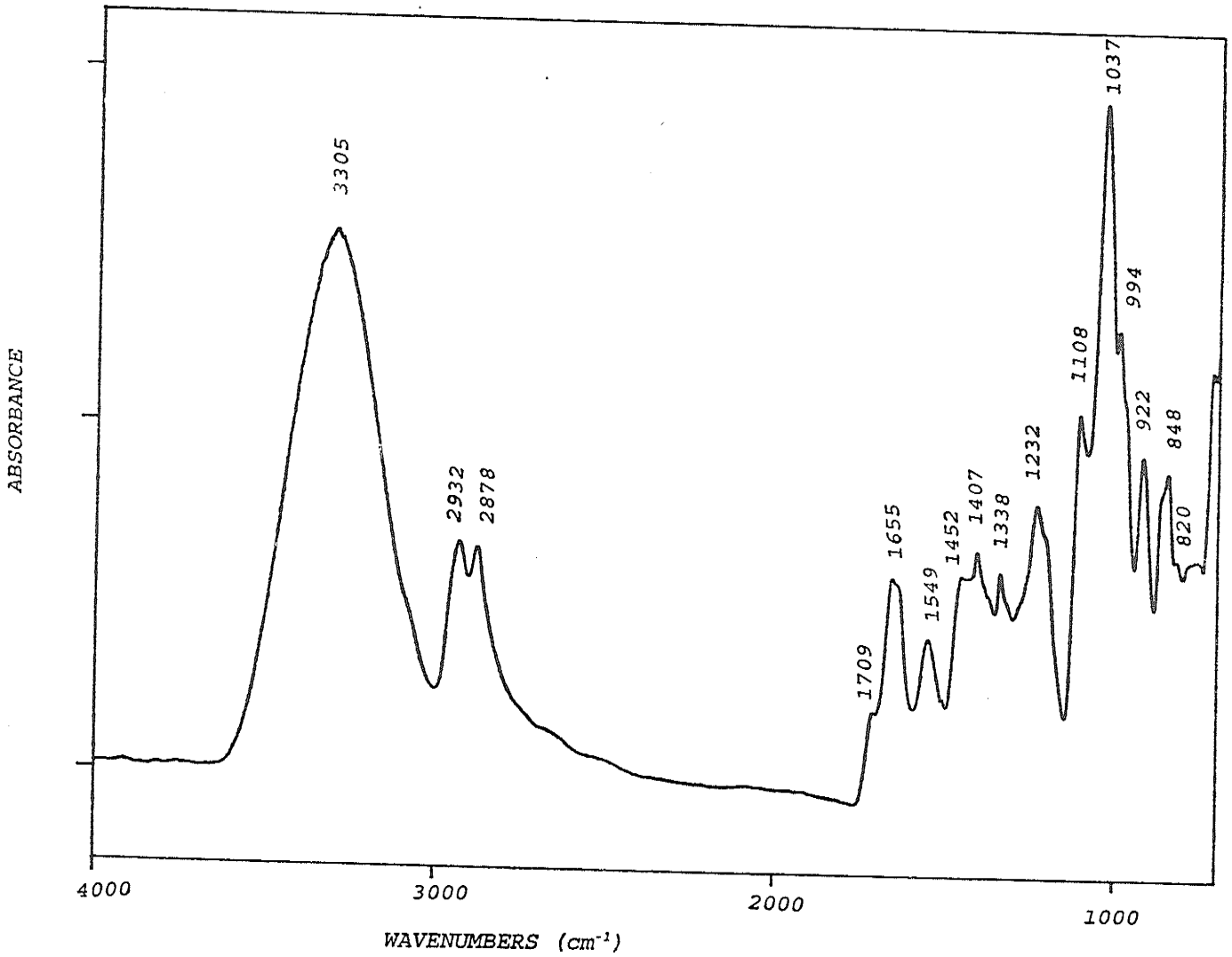


FIGURE 7C: INFRA RED SPECTRUM OF THE COLLAGEN COATED HEMASHIELD^{R} KNITTED PROSTHESIS.

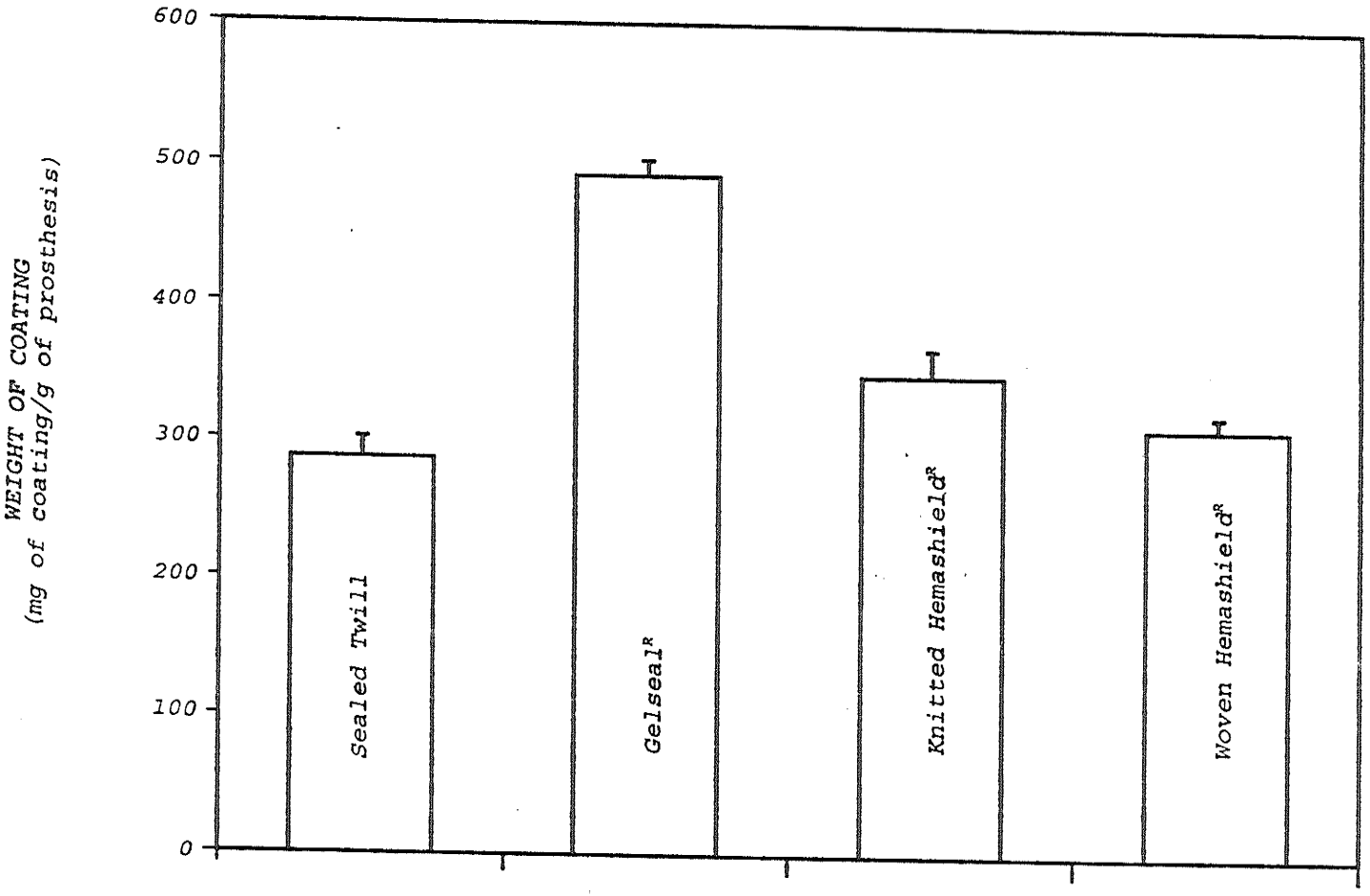


FIGURE 8: AMOUNT OF COATING ON THE SEALED PROSTHESES REPRESENTED AS BAR CHARTS.

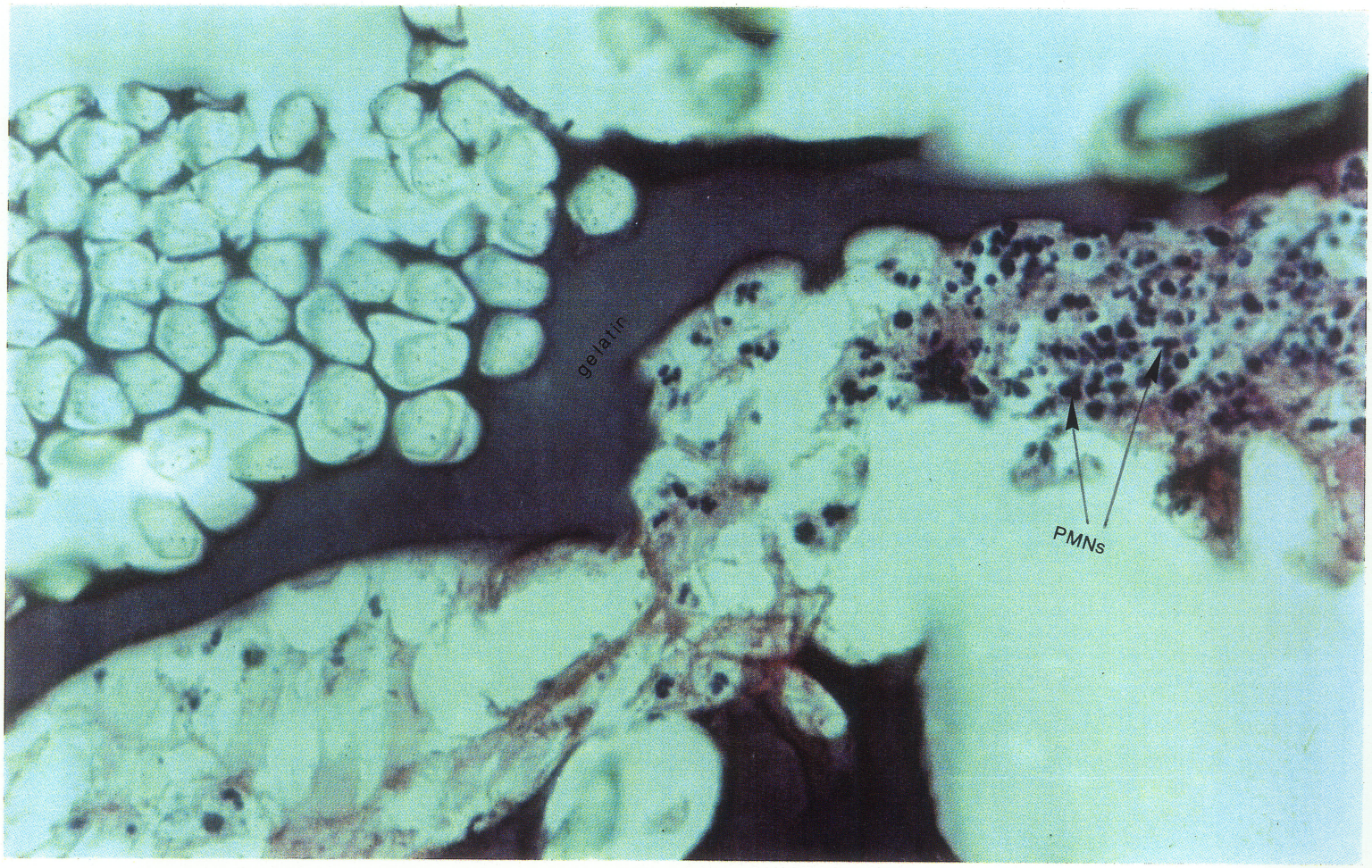


FIGURE 9: SEALED TWILL WOVEN GRAFT EXPLANTED AFTER 48 HOURS SHOWING MODERATE INFLAMMATORY REACTION IN CONTACT WITH THE GELATIN. POLYMORPHONUCLEAR CELLS AND LYMPHOCYTES ARE EASILY OBSERVED (X2500) (HEMATOXYLIN-EOSIN).

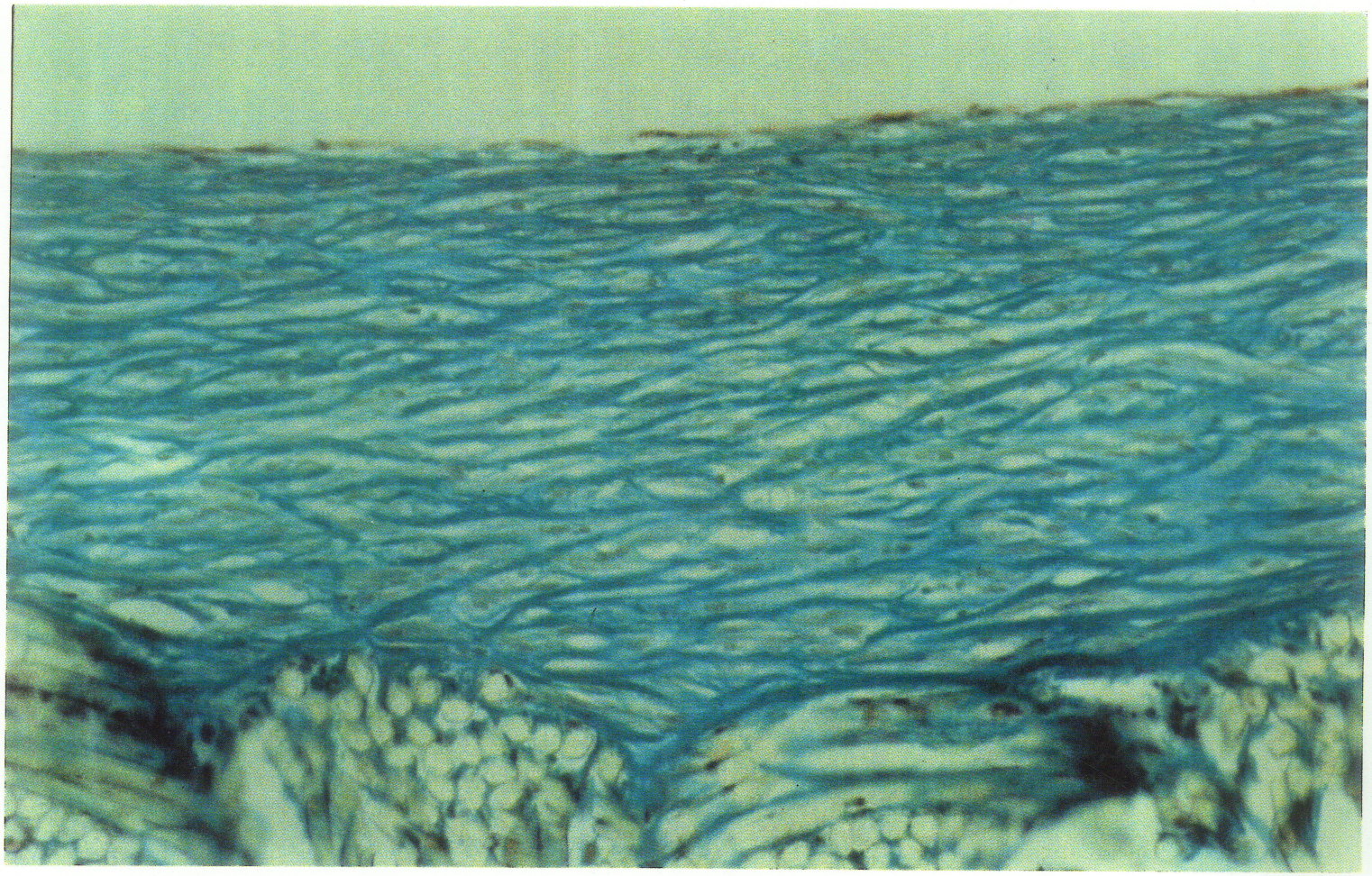


FIGURE 10: SEALED TWILL WOVEN GRAFT EXPLANTED AFTER 1 MONTH SHOWING THE NEOINTIMA OF NEWLY FORMED COLLAGEN AND SOME CELLULARITY ON THE FLOW SURFACE (X1250) (MASSON TRICHROME).

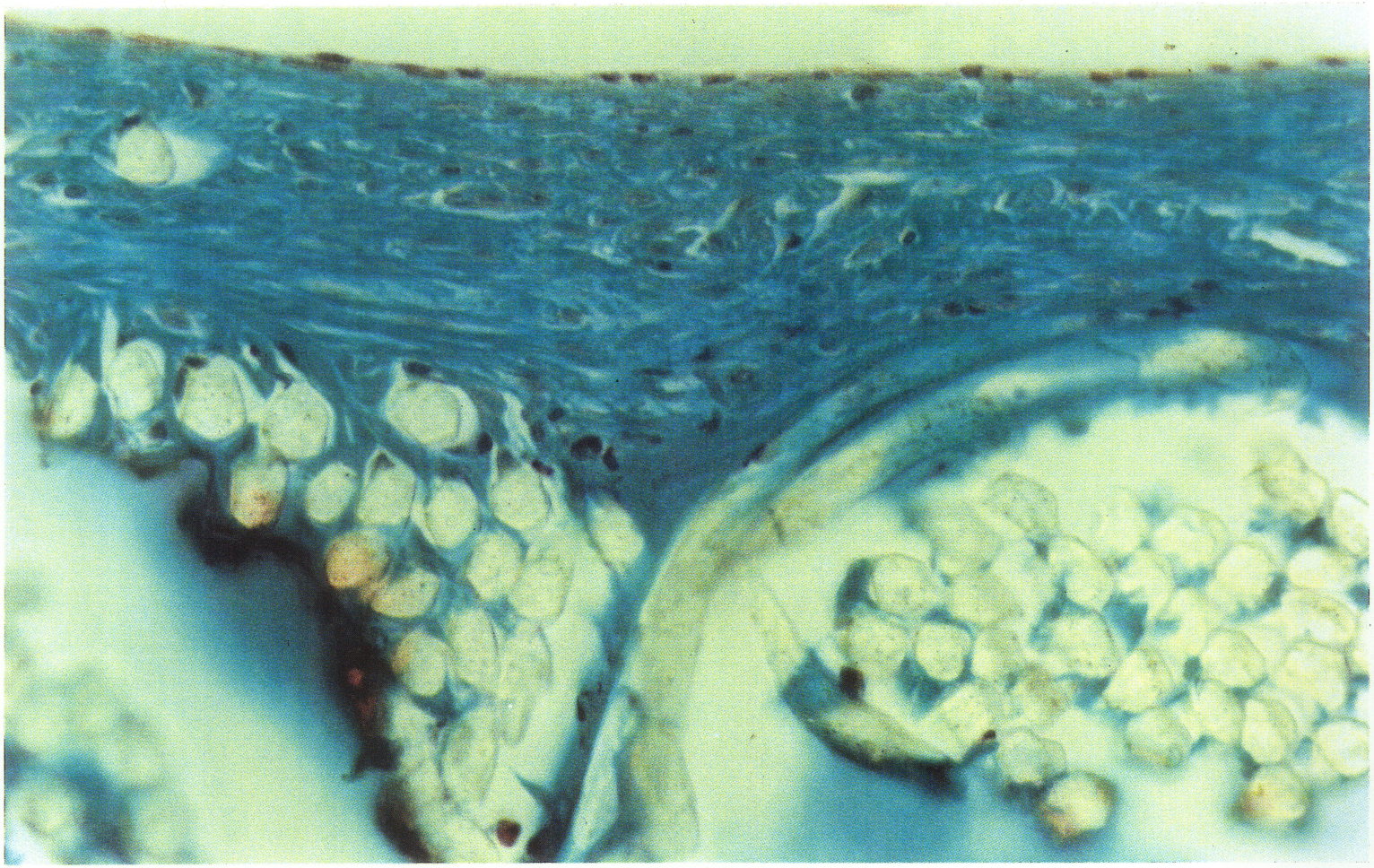


FIGURE 11: DISTAL PORTION OF SEALED TWILL WOVEN GRAFT EXPLANTED AFTER 6 MONTHS SHOWING THIN COLLAGENOUS CAPSULE WITH CELLULARITY AND A CONTINUOUS LAYER OF CELLS ON THE LUMINAL SURFACE (X1500) MASSON TRICHROME).

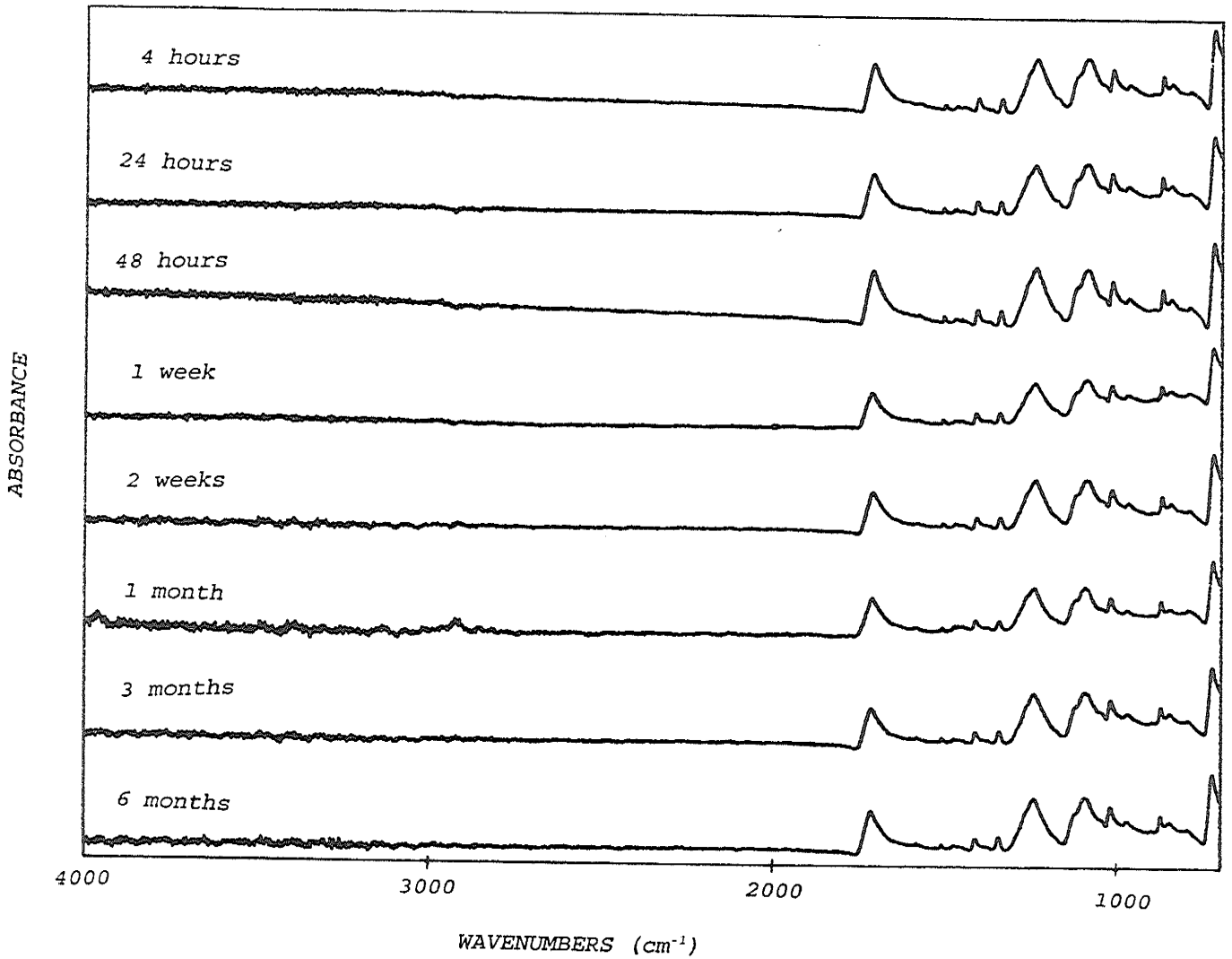


FIGURE 12: INFRA RED SPECTRA OF THE EXPLANTED SEALED TWILL WOVEN GRAFTS.

4. DISCUSSION AND CONCLUSION:

The purpose of this study was to evaluate the textile, physical and chemical characteristics of the new, prototype, Twill Woven prostheses and to test the hypotheses listed in section 1.1.3. The first hypothesis was that of no significant difference between the performance characteristics of the Twill Woven prosthesis and other prostheses with different weave constructions. Fifteen woven prostheses were selected and subjected to several tests including water permeability, dilation, suture retention strength and bursting strength measurements. Of all the prostheses evaluated, tightly woven taffetta type structures had the highest bursting strengths, lowest water permeability and dilation values. As the weave construction became more open, the bursting strengths decreased accordingly with a corresponding increase in water permeability and dilation values. With the Twill Woven prosthesis, the values obtained for the performance properties were similar to those of the control prostheses currently in use. However, a one way analysis of variance on the data obtained showed statistically significant differences between the water permeability, bursting and suture retention strengths (measured at 0° i.e. parallel to the longitudinal axes of the various prostheses) of the Twill Woven prosthesis and those of the control prostheses. The suture retention strengths measured at 45° and 90° respectively were, however, not significantly different for the various prostheses analysed.

The second hypothesis of no significant difference in the performance characteristics of the unsealed and sealed Twill Woven prostheses was tested by subjecting the data obtained for the performance properties of both prostheses to a one way analysis of variance. The gelatin coating effectively decreased the water permeability of the Twill Woven prosthesis from 80 to 0 ml min^{-1} cm^{-2} so that preclotting of the sealed variety prior to implantation is not required. This difference was

statistically significant. In addition to the reduction in water permeability, a slight increase was observed in the bursting strength of the sealed over the unsealed variety. However, this was not statistically significant. The suture retention strengths and the dilation of the sealed Twill were also not significantly different from those of the unsealed variety.

A third hypothesis was that of no significant difference between the performance characteristics of the sealed Twill Woven prosthesis and those of other sealed prostheses. The suture retention strength of the Twill Woven prosthesis was found to be significantly different from those of the sealed controls. Even the values obtained at different angles for each prosthesis differed significantly. In other words, the angle at which the suture retention strength was measured had an effect on this property. The bursting strength of the sealed Twill also differed significantly from those of the other sealed prostheses. In addition, its water permeability was significantly different from those of the collagen coated prostheses i.e. the Hemashield® knitted and woven prostheses. The only exception was the Gelseal® prosthesis which showed no significant difference in its water permeability characteristic to that of the sealed Twill Woven prosthesis. The surface morphologies of the sealed Twill and other sealed control prostheses were evaluated using scanning electron microscopy and the weight of coating on each prosthesis was determined. The coating weights differed significantly from one prosthesis to another. The sealant degradation rate for each type of prosthesis could not be determined due to the limited sample available for this study but the in vivo study showed that the gelatin coating on the Twill Woven prosthesis was completely bioeroded after two weeks of implantation. Previous studies[1-3] have also shown that the control prostheses had their collagen or gelatin sealants completely resorbed within one month of implantation.

The last two hypothesis were those of no significant difference between the performance characteristics of the virgin Twill Woven prostheses and those of the explanted prostheses. Bursting strength tests performed on the explanted and cleaned, unsealed and sealed prostheses, despite a limited amount of material available, indicated an increase in bursting strength which peaked at one week and then gradually decreased to its original value. This trend was observed with both the unsealed and sealed varieties. Statistical analyses could not be performed on the incomplete bursting strength data obtained, so that the last two hypotheses could not be tested statistically. However, thermal analyses of the cleaned, explanted prostheses showed no difference in the crystallinity indices and average peak melting temperatures of the explanted materials compared to the virgin prostheses, an indication that the microstructure of the polyester had not changed as a result of implantation. A six month implantation time may, however, not sufficient to determine the ultimate effect of implantation time on any prosthesis.

Infra red analyses of the cleaned explanted unsealed Twill Woven prosthesis showed some features which were absent in the infrared spectrum of the virgin prosthesis. These extra features may be attributed to the presence of biologic fluids and/or tissue which might have been picked up by the prosthesis during the cleaning process when the explanted prostheses were boiled with residual greasy tissue or during implantation in the bodies of the dogs. The infrared bands suggested that the foreign material on the unsealed Twill could be lipid molecules. The explanted and cleaned sealed Twill Woven prostheses did not show any of these extra infrared features even though they had been subjected to similar treatments as the unsealed variety. Many unanswered questions still exist at this stage but further studies, to determine whether lipid uptake occurred during implantation or during the cleaning process, are

continuing.

The results of this study showed that the unsealed Twill woven prosthesis had similar characteristics to those of the control prostheses but the type of weave construction did make a statistically significant difference in the performance characteristics of the various prostheses included in this study. In addition, the gelatin made a significant difference in the water permeability properties of the Twill Woven prostheses but not in other performance characteristics. Significant differences also existed between the performance properties of the sealed Twill and other sealed control prostheses. Although these differences in the performance properties of the prostheses evaluated were statistically significant, each of the new Twill Woven prostheses is expected to perform satisfactorily based on experiences from clinical trials.

The water permeability is a property which tells the surgeon whether preclotting is required prior to implantation. In general, prostheses having water permeability values lower than 350 ml min^{-1} cm^{-2} do not need to be preclotted prior to implantation. Both the unsealed and sealed Twill Woven prototypes met this requirement and so do not need preclotting prior to implantation. Also, the bursting strengths obtained for the prototype prostheses were similar to that of the control Meadox^{R} Woven Double Velour which had proved successful in the past and are, therefore, considered adequate to withstand the pulsatile blood pressure during implantation. The suture retention strengths were also adequate. Results from clinical trials show that prostheses with suture retention strength values greater than 20 Newtons generally perform satisfactorily in <u>in vivo</u> situations. Finally, the dilation of the new prototype prostheses were lower than 2% which is the maximum value expected for woven prostheses. Based on the above discussion, the new Twill Woven prototypes are expected to perform satisfactorily when implanted in

humans. Satisfactory performance is however, not dependent solely on the prosthesis type. Other factors like the status and progression of the disease as well as the attention paid in applying the appropriate surgical techniques are equally important.

4.1. RECOMMENDATIONS FOR FURTHER STUDY:

A replication of the in vivo study is recommended to provide sufficient explanted samples for analyses. The prostheses should be implanted for periods longer than six months so as to determine the long term biostability of the Twill Woven prostheses. Further study is also recommended to determine whether lipid uptake could be a problem with the Twill Woven prosthesis.

4.2. REFERENCES:

1. Guidoin R., Marceau D., Couture, J., Rao T.J., Merhi Y., Roy P. & De la Faye D. Collagen coatings as biological sealants. Biomaterials, 1989, 10: 156-165.

2. Guidoin R., Marceau D., Rao T.J., King M.W., Merhi Y., Roy P., Martin L. & Duval M. In vitro and in vivo characterization of an impervious polyester arterial prosthesis: the Gelseal Triaxial^{R} graft. Biomaterials, 1987, 8: 433-441.

3. Guidoin R., Merhi Y., Sigot M.F., Blais P., Rao T.J., Marceau D. & Paynter R. Collagen coated polyester arterial prostheses: an evaluation. Transplantation and Implantation Today, 1988, 5: 21-25.