ABSTRACT

Dattilo, Jr., Philip Paul. Knotless Bi-directional Barbed Absorbable Surgical Suture. (Under the direction of Martin W. King.)

With the objective of eliminating the adverse effects of traditional sutures, a novel knotless bi-directional barbed monofilament absorbable suture has been developed that does not require surgical knots for security.

First the study focused on developing a method for characterizing the individual barbs as well as the bi-directional barbs for the whole suture. The method proved effective in characterizing the individual barb's geometry in terms of cut angle, cut depth, and a calculated cut length, as well as characterizing the left and right sections of the knotless suture in terms of the distance between cuts and the number of cuts per unit length.

Second the study focused on developing an *in vitro* method to measure wound holding capacity. Wound holding capacity was measured in two ways, first by evaluating the load required to give a 2 mm of separation of tissue at the wound, and secondly by and evaluating the area of tissue separation at a given load. The wound holding capacity of a knotless barbed suture at 2 mm of separation was found to be 27.72 ± 8.32 N compared to a traditional monofilament knotted control suture of 15.25 ± 3.36 N. At a given load of 11.12 N the area of separation was zero compared to the traditional monofilament control suture that yielded an area of separation of 3.38 ± 2.37 mm^2. The study was effective in developing test methods for characterizing the knotless suture geometry as well as developing an experimental method for measuring wound holding capacity. No significant difference in wound holding performance was found among barbed suture samples cut at different barb angles.

Knotless Bi-directional Barbed Absorbable Surgical Suture

by
Philip Paul Dattilo, Jr.

A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Textile Management and Technology

Raleigh

November 2002

Approved by:

_____
Dr. Martin W. King, Chair of Advisory Committee

_____
Dr. Abdelfattah Seyam, Member Advisory Committee

_____
Dr. David Buchanan, Member Advisory Committee

To Kathryn Anne Rizzo for her support, patience, and love through the writing of my Master of Science thesis

Biography

I, Philip Paul Dattilo, Jr. was born on July 31, 1978 in Louisville, KY. My family was shortly transferred to Charleston, SC where I grew up playing in the local marsh lands and enjoying the beautiful Carolina beaches. In 1992 my family was again transferred to Wilmington, NC, another costal community that was easily adaptable. I graduated high school from John T. Hoggard in 1996 and attending college was my top priority.

In the fall of 1996 I decided to attend North Carolina State University in Raleigh, NC because it was an excellent technical school. At NC State I majored in Textile Technology at the world renown College of Textiles. Graduating in fall of 2000, I decided to extend my education and continue studying in the subject of textiles. An opportunity arose to pursue a new and exciting field of medical textiles under the supervision of Dr. Martin W. King, Ph.D. I am planning to graduate in the fall of 2002 with a Master of Science degree in Textile Management and Technology, with the majority of my graduate schooling focusing on biomaterials and biotextiles.

Acknowledgements

I would like to acknowledge Dr. Martin W. King for his advice and helpful hand in guiding me through the Masters program and in his continued support in helping me finish my thesis. I would like to acknowledge Olin Stewart of the Nonwovens Cooperative Research Center and Chad Graham for their technical assistances. I also would like to acknowledge Jeff Leung and Stan Bachelor of Quill Medical, Inc. for their helpful suggestions and advice as well as their generous donations of sutures to aid in the study. Finally, I would like to express my appreciation to the College of Textiles at North Carolina State University for its financial support.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Introduction

The art of wound closure has typically used sutures or some sort of suturing device. These traditional methods of wound closure use a braided or monofilament suture that requires the use of knots for suture and wound closure security. Knots create problems in suture and wound security as well as wound healing. Other methods of wound closure have been invented that do not require the use of sutures; such as, staples and tissue adhesive glues. These products, however, do not achieve equivalent mechanical properties or the healing characteristics of sutures, and so have only limited clinical applications.

A novel idea has recently been developed to adhere tissue at a wound or incision using a barbed monofilament suture that does not require a surgical knot. The suture's microscopic bi-directional barbs are in a helical formation along and around the circumference of the suture to interact with the tissue, keeping the wound closed. The preferred method of application requires that all or the majority of the suture be implanted subdermally, and with such a subcutaneous location it is preferable that the suture be made from an absorbable polymer. The most adequate material used for this particular application is the polymer known as polydioxanone. Polydioxanone is a semi-crystalline polymer that is melt-extruded in monofilament form and is broken down by hydrolysis *in vivo*.[1] Polydioxanone has been well researched and found to be a safe and effective suturing material. [1]

Polydioxanone is a suitable polymer for the knotless barbed suture application because the polymer has the appropriate hardness that permits the manufacture and formation of precise and reliable rigid barbs. The barbs are described as bi-directional because they start at the midpoint of the suture and run in opposing directions. It is believed that the geometry of the

barbs will influence how the barbs and the suture will interact with adjacent tissue under tension and control the biomechanical properties, such as the wound holding capacity.

There have been a number of attempts to manufacture and develop knotless barbed sutures over the past 57 years. [11, 32, 33, 34, 35] These reports focused primarily on the use of barbed sutures to maintain the apposition of ruptured tendons. The references found were preliminary clinical reports and a single US patent. However, no further studies or articles have been published on the wider application of a knotless barbed surgical suture for surgical use.

1.2 Problem Statement

The traditional use of a conventional suture requires the formation of knots in order to ensure adequate tissue holding capacity. The presence of knots, however, is known clinically and experimentally to cause a prolonged severe inflammatory response, scar tissue formation, and a significant decrease in suture strength at the knot site. Another disadvantage of knotted sutures is that it takes considerable time to tie the knot securely; thereby, prolonging the operation and the exposure to bacteria and other infectious materials.

Given these disadvantages for knotted surgical sutures it would be clinically advantageous to find a technique of using surgical sutures without relying on the presence of knots. In order to develop a useful knotless barbed suture a number of design features need to be defined and optimized. The features that are likely to influence tissue holding performance of the knotless barbed suture are the geometry or configuration of the barbs, the size of the suture, and the suturing technique. The parameters that characterize the barb geometry or configurations are the cut angle, cut depth, cut length, distance between cuts, and number of cuts per unit length.

1.3 Purpose of Study

The underlining goal of this research study focuses on finding the optimal configuration of the barbs on this novel knotless barbed suture that effectively maintains tissue apposition during applied tension across the wound. The purpose of the study is to find a barb configuration that maintains proper tissue apposition that is clinically acceptable under tension. In particular, the study will focus on 3 dependent issues, namely: 1) developing a technique to characterize barb geometry, 2) developing an *in vitro* test method to measure the wound holding capacity of an incision under tension, 3) evaluating the effect of barb geometry on tissue performance, and assessing which test method will yield the most reliable results in comparing the knotless barb suture using a modified running stitch method, to a monofilament control suture with the traditional interrupted stitch method.

In evaluating the knotless barbed sutures it would be desirable to compare the barbed suture with an equivalent traditional monofilament control suture. The size of the equivalent monofilament control suture will be a 4-0 rather than a 2-0 polydioxanone because it has a similar straight ultimate tensile strength to that of the size 2-0 knotless barbed polydioxanone suture. Along with the variable barb configurations, there are the different suturing techniques between the barbed suture and traditional methods of suturing. Suturing technique for dermal wound approximation using the barbed suture will be characterized by a modified running stitch method. The traditional sutures will use the suturing techniques of the interrupted stitch method requiring a surgical knot.

1.4 Objectives

Objective I: To establish an experimental method that will give reliable measurements of the geometry of the barbs in a knotless absorbable bi-directional barbed surgical suture.

Objective II: To establish an *in vitro* experimental method that will give reliable measurements of the tissue holding capacity and area of separation of a wound closed with surgical sutures.

Objective III: To determine whether the use of a knotless barbed suture will provide different tissue holding capacity and area of separation compared to an equivalent knotted surgical suture.

Objective IV: To determine whether different barb geometries of knotless barbed sutures will result in a change in tissue holding capacity and area of separation.

1.5 Definitions

1. Bi-directional barbed suture: Monofilament suture that has been micro-machined to insert barbs in a helical formation around the circumference of the suture. These barbs are bi-directional starting at the mid-point and facing each other (Figure 1).

Figure 1. Schematic of a bi-directional barbed surgical suture

2. Image analysis: Computer software developed to capture and manipulate a digitized image from a video camera and to analyze the image using different measurement tools. Such tools contain a calibrated ruler for distance measurements, angle tool for measuring angles, a particle analysis tool that measures black pixels to calculate area, and other tools such as zoom in and zoom out to aid in precise measurements.

3. Chamois leather: A chemically cross-linked and processed animal skin that is used as a skin simulant. It has similar biomechanical properties and a more uniform thickness than natural fresh dermal tissue.

4. Wound holding capacity: The maximum force that tissue can support across a closed wound when stressed at right angles to the incision direction without failing. Clinical failure is defined when 2 mm of separation is created across the wound.

5. Area of Separation: The area that is formed when a given force is applied across a closed wound. The area is measured by the image analysis system.

6. Interrupted stitch method: A traditional way of approximating tissue using a series of individual knotted suture loops that are placed along the length of the wound (Figure 2).

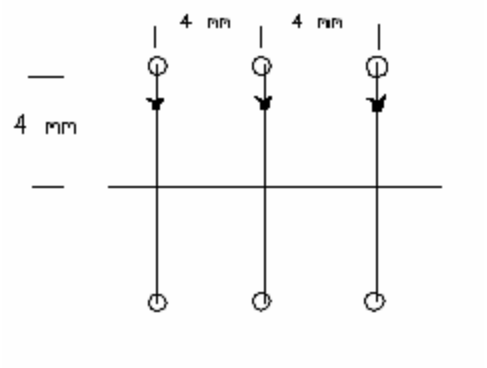

Figure 2. Schematic of the interrupted stitch method

7. Modified running stitch method: A novel way of approximating tissue using a continuous series of barbed suture loops without knots that are placed along the length of the wound (Figure 3).

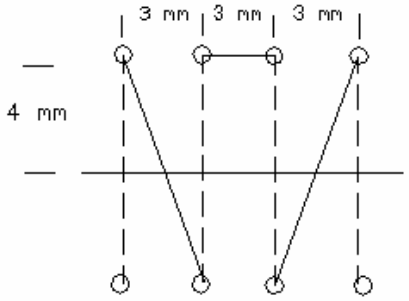

Figure 3. Schematic of the modified running stitch method

1.6 Limitations

The experimental statistical sampling of the knotless barbed and control sutures were not truly randomized. For both the barbed and control sutures the suppliers provided convenience samples for the study. Philip P. Dattilo, Jr. was responsible for preparing the sutured samples had little training in suturing techniques. This created additional variation during specimen preparation and increased variability when measuring the biomechanical properties.

2. Literature Review

2.1 Overview of Literature Review

This literature review will discuss the past and present forms of wound closure. The history of wound closure using sutures will be discussed as well as other forms of wound closure. Clinical techniques and applications of traditional sutures versus novel methods of tissue approximation will be discussed. This literature review will cover the problems associated with suture knots as well as the history and implementation of the knotless suture design. Finally, the literature review will discuss the bi-directional absorbable barbed surgical suture and its current applications.

2.2 History of Sutures in Wound Closure

Suturing materials and other methods of wound closure are used to aid approximation of tissue for the appropriate duration of the healing process. The use of sutures for tissue approximation is the oldest and still the most common form of wound closure.[2] The oldest known suturing material used on humans dates back to 1100 BC (implanted by the embalmer) and the oldest known suturing material used on live human tissue dates back to 600 BC.[3] These ancient sutures comprised of natural material such as linen, human hair, cotton, silk, and flax and did not change until the 1800's. Through the 1800's and into the 1900's rapid improvement and new materials were introduced into the field of sutures. By 1901, sutures could be found in the form of catgut and kangaroo gut (absorbable) kept in sterile glass tubes, gold and silver wire, silkworm gut, silk, cotton, linen, tendon and intestinal tissue from many forms of animals.[3]

The first synthetic sutures developed were non-absorbable sutures. These non-absorbable synthetic sutures are made from polymers such as, nylon, polypropylene, and polyester, and

various forms of metal wire. The first synthetic polymeric sutures were developed around 1930 to create less tissue reaction, drag, and scarring. Synthetic materials also reduced the risk of infection due to their ability to reduce the housing of bacteria during the healing process. The non-absorbable sutures require removal from the wound site at a specific time or suture marks and other adverse effects will occur. The use of non-absorbable sutures may be associated with additional surgeries and visits to the physician, and in these cases, absorbable sutures are advantageous. This is also true for some internal or sub-dermal wound closure techniques.

The precise date for the introduction of absorbable sutures for surgical application cannot be pinpointed. However, Joseph Lister's[3] work on catgut as a suturing material paved the way for the development of the absorbable suture. Catgut and most forms of preserved animal intestinal tissue are still used in surgery today. However, they come with some negative characteristics namely, non-uniform composition, unpredictable absorption rates, inconsistent breaking strength, and a prolonged tissue reaction that can hinder the healing process.[4] Due to the negative properties of catgut, a synthetic material was sought after to withstand the harsh environment of wound healing and maintain the required tensile properties.

In 1960 work began on developing synthetic absorbable sutures using polymeric technology. Scientists had to create a polymer that was non-toxic to the body, degrade in an appropriate time, and had minimal tissue reaction. Frazza and Schmitt first synthesized polyglycolic acid and tested the material that yielded positive absorption characteristics.[5] The polyglycolic acid multifilament braided suture became known as Dexon® and in 1970 it was accepted by the Food and Drug Administration and released for general surgical use as

the first polymeric absorbable suture material.[4] In 1975, another absorbable material was introduced for surgical wound closure. This braided multifilament suture was chemically comprised of a lactic acid glycolic acid copolymer known as polyglactin. This suture later became known as Vicryl®.[6]

The braided structure of Dexon® and Vicryl® has been found to provide sufficient wound holding characteristics. However, their structure can interfere with the healing process. The multifilaments sutures come with several negative aspects for wound closure and management since they tend to cause an intense inflammatory response, create a capillary action that causes infection to spread throughout the wound, and harvest bacteria between the strands.[7] Multifilament braided sutures can also create scar formation, resulting in negative cosmesis.[8] Due to the negative characteristics of braided or multifilament sutures, synthetic monofilament absorbable sutures were created to combat these disadvantages.

Researchers took the existing molecular structures of Dexon® and Vicryl®, and manufactured monofilament sutures. These attempts yielded stiff monofilament sutures due to their crystalline molecular compositions. As a result monofilament Dexon® and Vicryl® could only be used in fine deniers and were largely restricted to ophthalmic and microsurgical procedures.[9] In 1981, a new polymer called polydioxanone was introduced for surgical applications. It was a synthetic absorbable monofilament suture with improved handling capabilities from that of its monofilament predecessors, Dexon® and Vicryl®. Polydioxanone trade name PDS® was found to maintained sufficient strength throughout the healing process. It possessed improved handling characteristics, and caused minimal tissue inflammation.[9] The newer form of PDS® is PDS II®. This variation to the original polydioxanone suture has reduced stiffness and handling properties, while maintaining

superior tensile characteristics.[7] In 1985, the newest form of a synthetic absorbable monofilament suture extruded from the polymer polytrimethlyene carbonate (trade name Maxon®), was introduced. It is claimed to provide the ultimate tensile strength of PDS® with improved handling characteristics.[10]

Other innovative designs are being implemented within the field of suture technology. Examples of the designs consist of anti-microbial coatings and a novel idea of manufacturing "barbs" into a monofilament absorbable suture. Implementation of "barbs" for implantable device purposes originated in 1945, when barbed tubes were used for tendon repair.[11] In 1994, Dr. Gregory Ruff, M.D., of Duke Medical Center introduced an absorbable knotless barbed tissue connecting device designed to approximate tissue. The design described in U.S. Patents 5,342,376 [12] and 6,241,741 B1 [13] utilizes microscopic barbs that are manufactured onto the circumference of the tissue connector body. These barbs act as anchoring devices that keep the wound closed and prevent dehiscence without the use of knots. The idea of a knotless wound closure device has evolved from the barbed tissue connector with the development of an absorbable monofilament polydioxanone suture.

The goal of wound closure is to apply a material and method to approximate tissue for the duration of the healing process. The earliest form and still the most common material for wound closure is the surgical suture. Today many forms of sutures are on the market that are engineered and used for very specific applications. In 1999, the number of surgical interventions created a market size of 210 million dollars in sutures sold in the United States alone.[14]

2.3 Technical Applications of Sutures for Wound Closure

Currently on the market there are two categories of sutures: absorbable and non-absorbable. The application of the two categories depends on the type of procedure and the physician's preference. Figure 4 shows the current absorbable and non-absorbable sutures on the market as of 1997[1].

There are primarily four categories for classifying the use of sutures: dermal closure, internal closure, tendon repair, and fastener. Dermal closure uses the suture to approximate the tissue at the site of the wound. Absorbable sutures predominate mostly in internal wound closure. Internal closure from a wound or incision uses an absorbable suture because it eliminates additional surgical procedures that would be needed for removal of non-absorbable sutures. Tendon repair uses sutures to join the two-ruptured ends of the tendon or ligament. Either absorbable or non-absorbable sutures are used in this procedure. Finally, sutures can be used as fasteners to attach implantable devices to their intended position. An example of this can be seen in US Patent 6,085,754 [15], where sutures are used to fasten a warp knitted polyester cardiac support jacket around the heart to restrict expansion of a diseased heart.

Dermal and internal wound closure requires the physician to decide on a specific type of technique for approximation of the wound edges. The type of suturing technique depends on the configuration of the wound, the environment of the wound, and the type of physical properties the wound shape will inflict on the suturing material.[7] An ideal

Generic name	Trade name	Physical configuration	Surface treatment	Manufacturer*
		Natural Absorbable Sutures		
Catgut	Catgut or surgical gut	Twisted multifilament	Plain and chromic	A, E, D/G, SSC
Catgut	Surgigut®	Twisted multifilament	Plain and chromic	USS
Catgut	Softgut®	Twisted multifilament	Glycerin-coated	D/G
Reconstituted collagen	Collagen	Twisted multifilament	Plain and chromic	E
		Synthetic Absorbable Sutures		
Polyglycolide	Dexon "S"®	Braided multifilament	None	D/G
Polyglycolide	Dexon Plus®	Braided multifilament	Poly(oxyethylene-oxypropylene)	D/G
Polyglycolide	Dexon II®	Braided multifilament	Polycaprolate	D/G
Polyglycolide	Medifit®	Braided multifilament	None	JPS
Poly(glycolide-L-lactide) (polyglactin 910)	Vicryl®	Braided multifilament	Polyglactin 370 and calcium stearate	E
Poly(glycolide-L-lactide)	Polysorb®	Braided multifilament	Coated	USS
Poly-*p*-dioxanone	PDS II®	Monofilament	None	E
Poly(glycolide-co-trimethylene carbonate)	Maxon®	Monofilament	None	D/G
Poly(glycolide-co-ε-caprolactone) (poliglecaprone 25)	Monocryl®	Monofilament	None	E
Glycomer 631	Biosyn®	Monofilament	None	USS
		Nonabsorbable Sutures		
Silk	Surgical Silk®	Braided multifilament	Tru-permanizing	E
Silk	Dermal®	Twisted multifilament	Tanned gelatin (or other proteins)	E
Silk	Virgin Silk®	Twisted multifilament	—	E
Silk	Silk	Braided multifilament	Silicone	E, D/G
Silk	Sofsilk®	Braided multifilament	Coated	USS
Silk	Silk	Braided multifilament	Paraffin wax	SSC
Cotton	Surgical cotton	Twisted multifilament	—	E
Cotton	Cotton	Twisted multifilament	—	D/G
Linen	Linen	Twisted multifilament	—	SSC, E
Polyester	Ethibond®	Braided multifilament	Polybutylate	E
Polyester	Mersilene®	Braided multifilament	—	E
Polyester	Ethiflex®	Braided multifilament	Teflon	E
Polyester	Dacron®	Braided multifilament	None	D/G
Polyester	Ti-Cron®	Braided multifilament	Silicone	D/G
Polyester	Surgidac®	Braided and monofilament	Coated with braid	USS
Polyester	Silky Polydek®	Braided multifilament	Teflonized	SSC
Polyester	Sterilene®	Braided multifilament	Teflonized	SSC
Polyester	Tevdek®	Braided multifilament	Teflonized	SSC
Polyester	Astralen®	Braided multifilament	Teflonized	A
Polyester	Polyviolene®	Braided multifilament	—	L
Polyester	Mirafil®	Monofilament	—	BM
Polyester	Novafil®	Monofilament	None	D/G
Polyamide (nylon 6 and 66)	Ethilon®	Monofilament	—	E
Polyamide (nylon 6 and 66)	Nurolon®	Braided multifilameat	Coated	E
Polyamide (nylon 66)	Surgilon®	Braided multifilament	Silicone	D/G
Polyamide (nylon 66)	Dermalon®	Monofilament	None	D/G
Polyamide (nylon 66)	Bralon® monosof®	Braided monofilament	Coated	USS
Polyamide	Sutron®	Monofilament	—	SSC
Polyamide (nylon 6)	Supramid®	Core-sheath	—	A
Polypropylene	Prolene®	Monofilament	—	E
Polypropylene	Surgilene®	Monofilament	None	D/G

*** Note: A, Astra; E, Ethicon; L, Look; D/G, Davis & Geck; SSC, Society Steril Catgut; BM, Braun Melsungen; JPS, Japan Medical Supply; USS, US Surgical**

Figure 4 [1]. List of Absorbable and Non-absorbable sutures

wound closure will leave little scar tissue and suturing marks. The most common forms of suturing technique for dermal and internal wounds are the running subcuticular suture, the interrupted suture, vertical mattress suture, half buried horizontal suture, superficial interrupted suture through a flat tip, horizontal mattress suture, and running subcuticular suture (See Figures 5 thru 7).[7] Yet another suturing technique has been characterized as

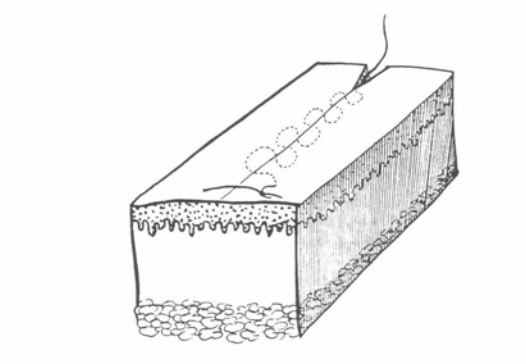

Figure 5[7]. Running subcuticular suture

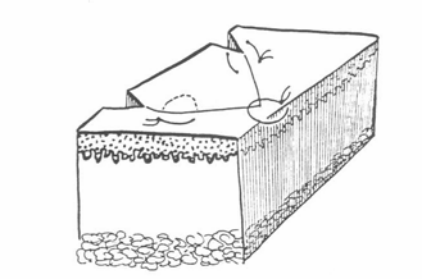

Figure 6[7]. Half buried horizontal suture, superficial interrupted suture through flap tip, and horizontal mattress suture

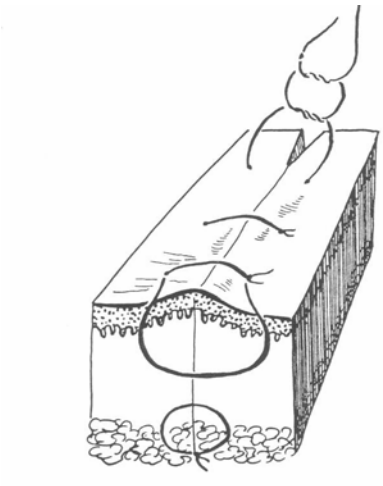

Figure 7[7]. Interrupted suture

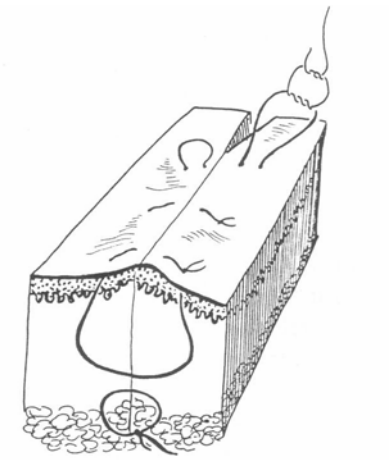

Figure 8[7]. Vertical mattress suture

the buried vertical mattress suture (Figure 8). This technique greatly reduces scar tissue and creates a high degree of patient satisfaction (the patient cannot actually see the suturing material).[16] Procedures for tendon and ligament repair use sutures that run through each ruptured end, pull the ruptured ends together, and are fastened with knots or other methods. One method used to repair a ruptured Achilles tendon, for example, uses the combination of three 2-0 wire sutures with a barb soldered half way along the sutures, and rubber stoppers (Figure 9). [17]

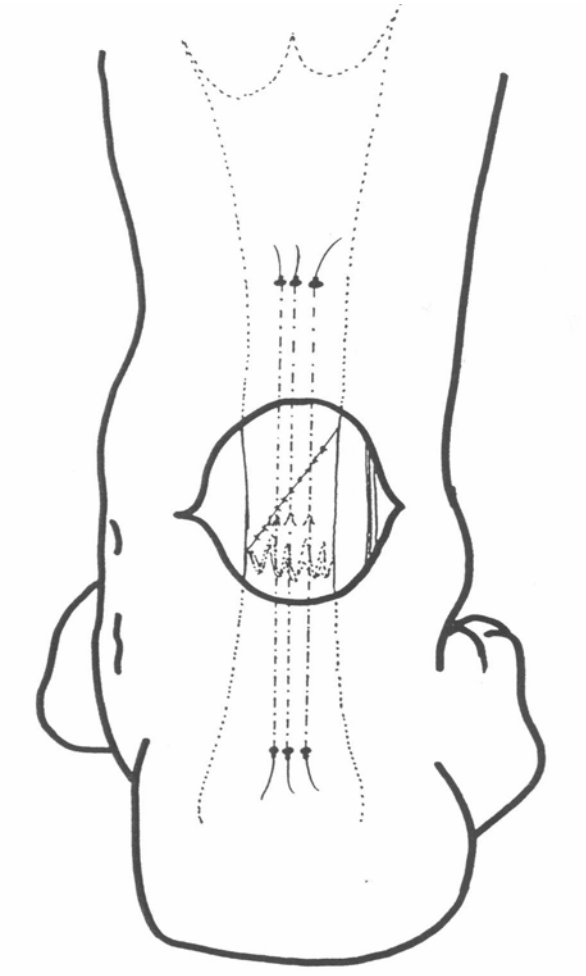

Figure 9 [17]. The ruptured Achilles tendon is brought together by the use of steel wire surgical sutures

The use of sutures requires some form of surgical knot to fasten the suture into place. The perfect combination of material and suture technique is worthless unless the tissue is

approximated and held for the appropriate duration of the healing process.[18] Surgical knots are the only way to hold sutures in place. However, as reported earlier, they come with adverse effects.

2.4 Mechanical, Inflammatory, and Cosmetic Problems Associated with Surgical Knots

Sutures are the largest market for wound closure, yet there is no standard method for securing them. There is ample literature on the mechanical and tissue response of surgical knots. However, the literature tends to contradict itself in terms of the type of knot to be used for specific surgical procedures.[19] The contradiction is not only in the literature, but also between surgeons and physicians. The literature describes numerous methods and types of knots for suture security (Figure 10). The disagreement in the type of knot to use can be attributed to the fact that knot tying is not discussed openly in surgery.[20]

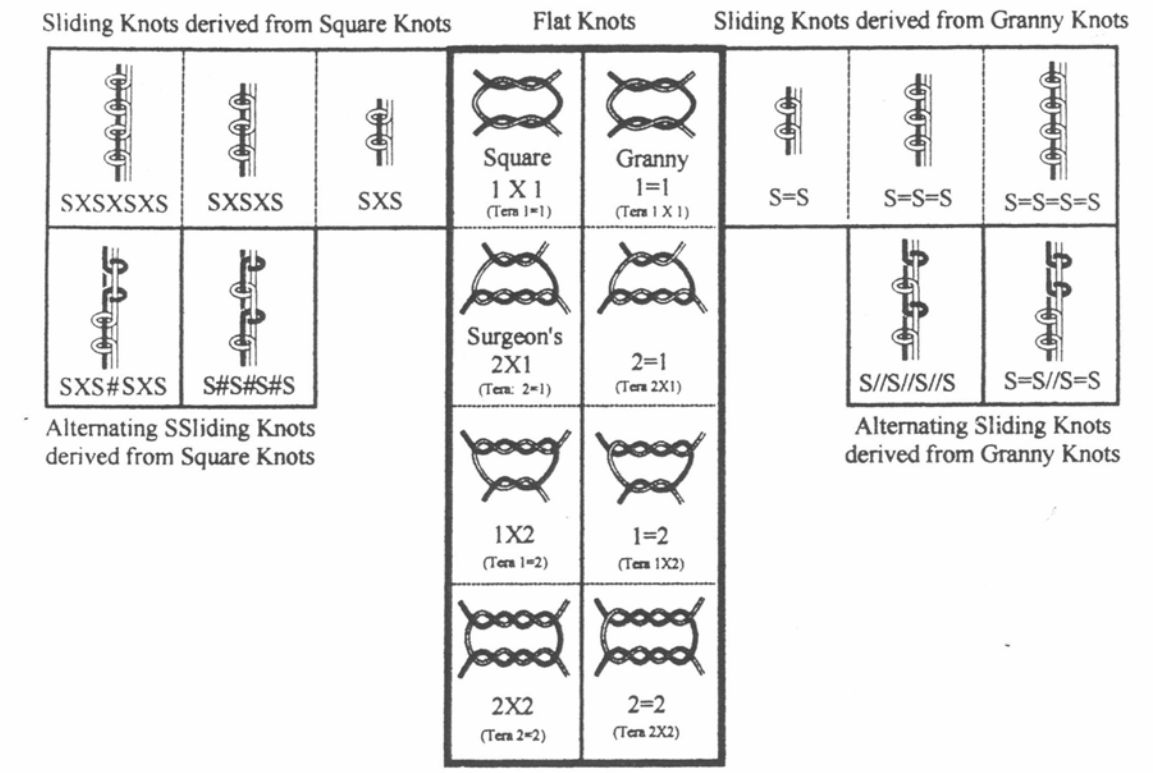

Figure 10 [18]. Formation of various surgical knots

Surgical knots are created by entangling the suture in a way that creates enough frictional forces to keep the knot and suture in place. Knot formation requires special attention because the majority of suture failures occur at the knot site.[21] The knot site creates a tremendous amount of shear and bending forces on the suture. Shear and bending forces are the major contributors to suture failure at the knot site, which can lead to possible dehiscence of the wound.[18] Mechanically, the localized knot site creates major problems due to the inherent weakening of the suture when and where a knot is applied.

The human body does not react well to foreign material and knots create a large volume of foreign material. The major cause of the inflammatory response can be attributed to the knot.[22,23] In addition, the knot can harvest and hide bacteria. The inflammatory response in conjunction with scar tissue causes adverse cosmetic results, thus creating patient dissatisfaction. Surgical knots have the ability to cause major problems for wound healing and potentially produce negative cosmesis. Consequently investment in new technologies and research has attempted to find alternative methods for wound closure which do not require the use of surgical knots.

2.5 Alternative Knotless Methods of Wound Closure

Advancements in wound closure have produced various applications of wound closure materials and methods. Staples, glues, tape, and "zip-ties" (Sterna-band®) have been introduced to reduce the time of operation and problems associated with knots. Staples are used to reduce operation time and are believed to reduce tissue trauma.[24] Cyanoacrylate glues[25] and adhesive tape[26] are growing in popularity, especially in the field of pediatrics because they involve less invasive procedures. However, glues and tape tend to be ineffective in areas of high tension. Sternotomy closure techniques have typically used

suturing material, but a new method of wound closure has been developed using a knotless material called Sterna-band®[27] (Figure 11).

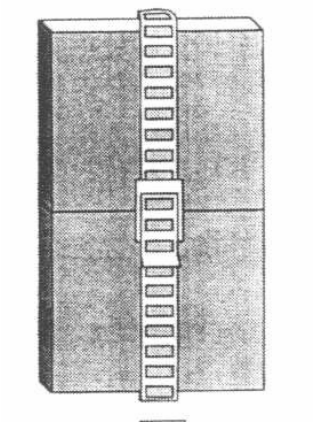

Figure 11[27]. Diagram showing the working principle of Sterna-band®

Another method of wound closure has recently been developed that uses suturing material, which is held in place by microscopic barbs. These barbs interact with the tissue and act as anchoring devices keeping the wound securely closed. This technologically advanced suture uses bi-directional barbs on the circumference of an absorbable suture. The barbs allow the suture to be completely knotless when used as a wound closure device.

2.6 Bi-directional Barbed Absorbable Suture

Many implantable materials have used barbs in a range of different or surgical applications. The main use of barbs has been for stability of structures. Barbs act as anchoring devices that prevent migration of the specific device. Such applications have been used in stent-grafts [28, 29] to keep the stent-graft attached to the desired site and prevent migration. Several US patents describe the use of barbs in devices that connect tissue[12,13,30], that are used as anchoring devices for connecting the first and second vessels in an anastomosis [31], and that create self-anchoring suturing materials.[32] As described previously, barbs have been used in Achilles tendon repair. Barb were soldered onto the steel wire to aid

in holding the ruptured tendons together.[17,33,34] Applying barbs to suturing materials is advantageous because it has the ability to approximate the tissue of a wound without the use of surgical knots and the adverse effects that are associated with knots.

The idea of adding barbs to a monofilament absorbable suture was first proposed by Dr. Gregory Ruff of Duke Medical Center, Durham, NC in 1992. However, a similar idea had been evaluated in 1967 for the use of tendon repair of the hand and fingers [35] (Figure 12) and a US patent [32] was granted in 1964 to "roughen" the surface of the

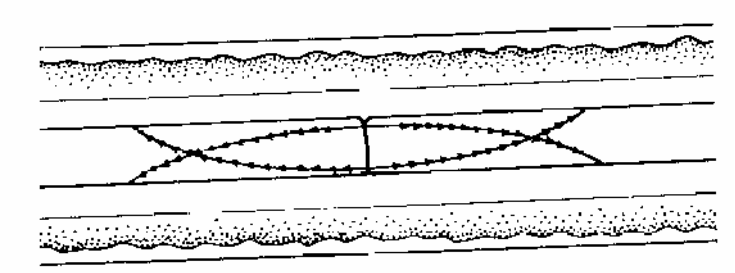

Figure 12[35]. Barbed suture applied to repair a tendon in the hand

suturing material to prevent slippage. Dr. Ruff's idea was to apply microscopic bi-directional barbs in a spiral pattern around the circumference of an absorbable suture.[36] The suturing material used for this application was polydioxanone because it is an absorbable material and has the appropriate hardness to allow the creation of rigid barbs by a micro-machining process. An absorbable material is preferred because it is used predominately in sub-dermal applications where a second intervention for suture removal is undesirable.

The stitch method used for the bi-directional absorbable suture in dermal tissue repair depends on the size, the shape, and the depth of the wound. Several stitching techniques for dermal repair have been developed such as the, alpha, zigzag, coil, and modified running stitch methods (Figures 13 thru 16). In addition to dermal repair, methods have been developed for tendon repair using the "Finger-trap" method (Figure 17) and the

"Switchback" method (Figure 18). The absence of knots reduces the time of the intervention and decreases the intensity of the tissue inflammatory response.

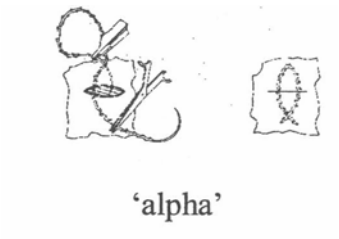

Figure 13. Alpha suturing technique using bi-directional barbed suture

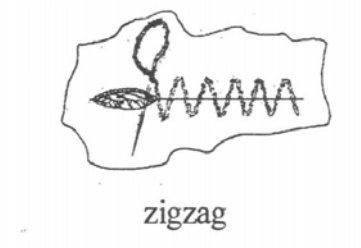

Figure 14. Zigzag suturing technique using bi-directional barbed suture

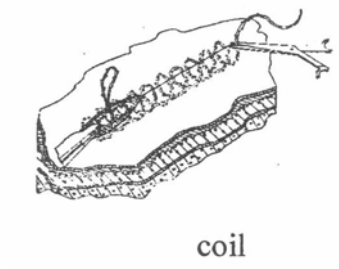

Figure 15. Coil suturing technique using bi-directional barbed suture

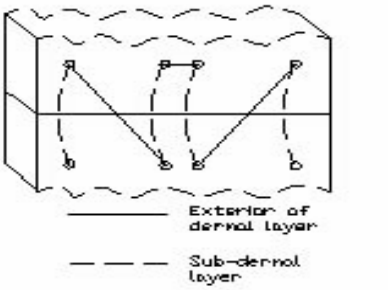

Figure 16. Modified running suturing technique using bi-directional barbed suture

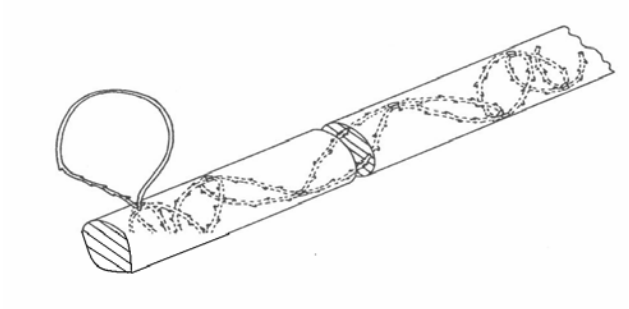

Figure 17. Finger trap suturing technique for tendon repair

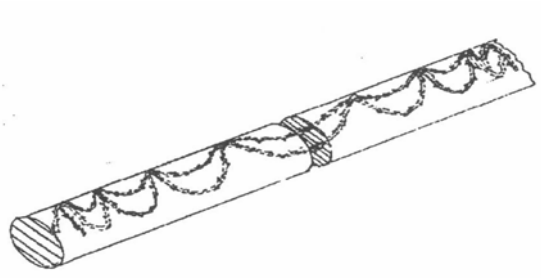

Figure 18. Switchback suturing technique for tendon repair

Over the years, suturing materials have evolved from simple strands of natural material to specifically engineered polymeric biomaterials. Synthetic braided sutures are still used today, but can lead to infection and other adverse effects. Monofilament sutures are used to reduce the inflammatory response, but require the use of surgical knots. These traditional sutures require knots for security, which can cause problems in the healing process. It is anticipated that the design and development of knotless bi-directional barbed absorbable sutures may well have a positive impact on the clinical outcomes of wound closure and tendon repair in the future.

3. Materials and Methods

3.1 Materials

The monofilament sutures used in this study were made of the polymer polydioxanone [Figure 19]. They were manufactured and provided by Quill Medical, Inc (Research

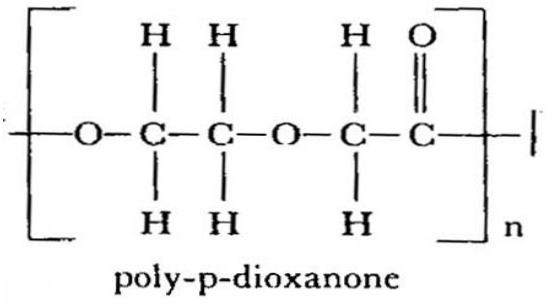

Figure 19. Chemical structure of the polymer polydioxanone

Triangle Park, NC). The bi-directional barbs were micro-machined size 2-0 sutures (0.30-0.39 mm in diameter) with three different barb geometries, that is, having low, medium, and high cut angles (see list below). In addition a size 4-0 (0.20-0.24 mm in diameter) control polydioxanone suture (PDS II ®, Ethicon) was included in the mechanical testing procedures. A size 4-0 monofilament control suture was used in comparison to the size 2-0 knotless barbed suture because of the similar ultimate tensile strengths under straight tension. The suturing materials used for this study are listed as:

1) Size 2-0 polydioxanone knotless barbed sutures with 18 mm curved cutting needle at both ends
   A) Lot # 1-SDB-6A (low cut angle)
   B) Lot # 1-SDB-5A (medium cut angle)
   C) Lot # 1-SDB-5B (high cut angle)
2) Size 4-0 polydioxanone monofilament (Control Suture) with 17 mm curved taper needle at one end

3.2 Methods for Measuring Suture Geometry

3.2.1 Characterizing Individual Barbs and Bi-directional Barbed Suture Geometry

Initially the various geometric parameters of the individual barbs and the bi-directional barbed suture as a whole were characterized. The objective of these tests was not only to define the barb and suture geometry, but also to establish the typical manufacturing variability within and between sutures.

Each suture was divided about its midpoint into two sections; one called right (R) and the other called left (L), with the barbs facing in opposite directions in each. Each R and L section contained 39 barbs. The R and L sections were divided into four regions, which were measured separately so as to determine whether the barb geometry changed along the length of the monofilament from the middle portion to the two needles. The geometry of four barbs were measured in each region. Region one (R1) contained barbs 1 thru 4, region two (R2) contained barbs 13-16, region three (R3) contained barbs 24-27, and region four (R4) contained barbs 36-39. The geometry for each individual barb was characterized in terms of its cut angle, cut depth, and calculated cut length. The term "cut" is used to describe how the formation of the barb occurred.

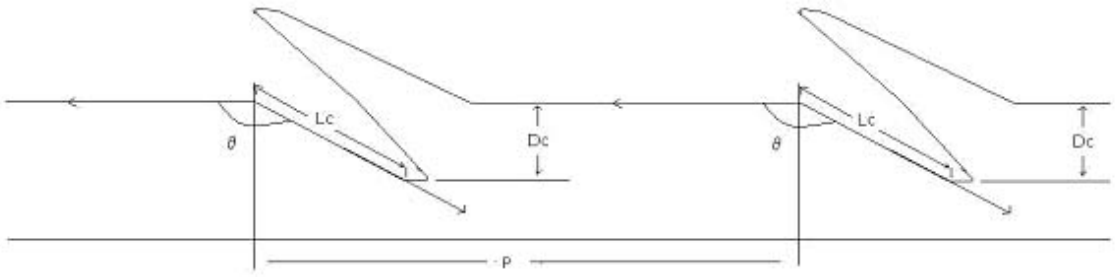

Figure 20. Schematic of two consecutive barbs showing the different geometric parameters.

The method for measuring the cut angle and cut depth are shown in Figure 20 where θ is the cut angle, L_c cut length, D_c cut depth, and P is the distance between cuts.

The cut length measurement was then calculated using the following equation:

$$L_c = \frac{D_c}{\sin(180 - \theta)}$$

Once the geometries of the individual barbs in the four regions of the L and R sections had been collected, the distance between cuts (P) and the number of cuts per unit length was then measured. First, twist was inserted into one end of the suture in an attempt to "line-up" the cuts. After the twist had been inserted and the cuts were aligned along the suture axis, the distance between cuts (P) and the number of cuts per unit length was measured [Figures 20 and 21].

Figure 21. Aligned barbs for measuring the distance between cuts and number of cuts per unit length measurement

3.2.2 Measuring Individual Barb and Bi-directional Barb Suture Geometry

The suture was mounted in a yarn/suture mounting device and placed under an Aoptem Zoom 100 custom microscope that is interfaced with the Image Analysis System version 3.0 [designed by Behnam Pourdeyhimi, North Carolina State University]. Images of the individual barbs were taken using the Aoptem Zoom 100 custom microscope with ring and back lighting at a setting of 6.0 and magnification of 22x [Figure 22].

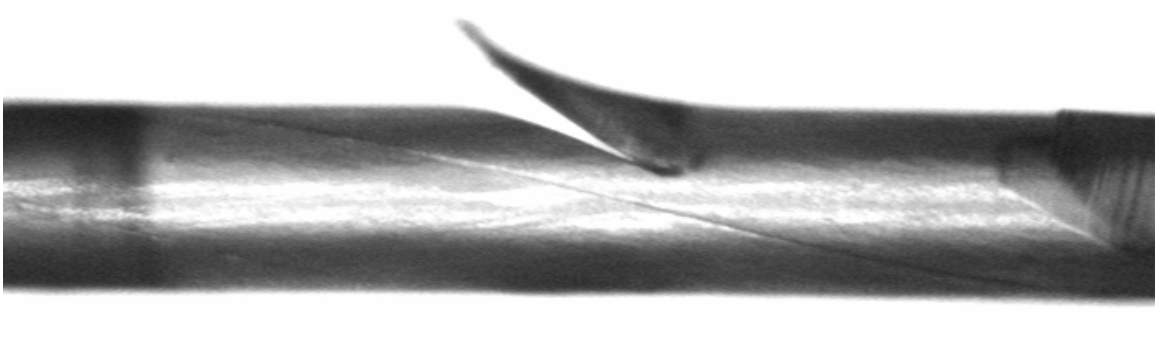

Figure 22. Image of individual barb used to measure cut angle and cut depth

The images of the individual barbs were stored in the image analysis system. The images of the individual barbs of the four regions for R and L were measured for cut angle and cut depth using the calibrated angle measurement tool and ruler tool of the image analysis system. The cut angle was measured in degrees and the cut depth in mm. The microscope was then adjusted to a setting of 1.0 and magnification 4x so as to measure the distance between cuts and the number of cuts per unit length. The rotating end of the mounting device inserted the twist. The addition of twist orientates the barbs in an aligned position along the suture axis [Figure 21]. Using the recalibrated ruler tool the distance between cuts and the number of cuts per unit length was determined.

When calculating distance between cuts and number of cuts per unit length the images did not capture each region, but viewed the R and L sections as a whole. This was done because these measurements did not relate to an individual barb, but the measurement of distance between barbs in the R and L sections.

These measurements were then transferred, stored, and manipulated in a Microsoft Excel spreadsheet. The cut length was calculated using the equation described above. The mean and standard deviation of each region were then calculated for each region. Single factor one-way ANOVA test were performed on the data at a confidence interval of 95% so as to

identify if there were significant differences between regions along the sutures in the same lot. The averages and standard deviations of the cut angle and cut depth were graphed for visual comparison. This procedure was followed for the three sutures specimens in each lot and for all three barbed suture lots in the study.

3.3 Methods for Measuring Wound Holding Capacity

3.3.1 Experimental Procedure for Wound Holding Capacity

The literature does not define a standard method for testing suture holding performance as applied to a wound or incision. An example of a clinical definition for wound holding capacity is the ability of a suture material to hold approximated tissue together until a failure point of 2 mm of separation has occurred at any point along the incision or wound line. The following experimental method has been developed with the objective of measuring this property by two separate techniques. It was decided to measure wound holding capacity using a tissue simulant rather than fresh natural tissue.

Due to the fact that human tissue was unavailable, attempts were made to harvest fresh animal dermal tissue from pigs due to their human like tissue characteristics.[38] However, the fresh porcine tissue was unsuccessful in providing consistent and uniformly thick tissues for mechanical testing. As a result a chemically cross-linked chamois leather product (Darra®, Van Nuys, CA) was used as a tissue simulant. Its consistency of tissue structure, availability, uniform thickness (approximately 2 mm), and ease of handling made it a suitable simulant for performing repetitive mechanical tests.

Stencils were designed to create consistent specimen shapes for mechanical testing by clearly defining the incision points, distances between bites, and the distances between the bites and the incision line. Two different stencils were designed, one for the knotless barbed

suture and the other for the monofilament polydioxanone control suture. The stencils were created in a "dog-bone" shape so as to ensure an effective force distribution during mechanical testing [Figure 23]. [39]

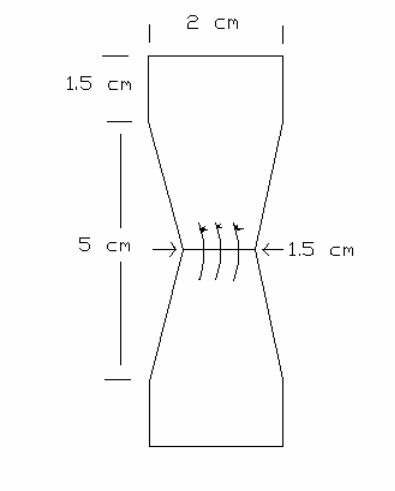

Figure 23. "Dog bone" shape specimen showing location of incision and sutures

It was anticipated that the shape would isolate the closed incision with the attached sutures and help prevent jaw slippage by giving the specimen more surface area at the jaw site.

The suturing technique used for the knotless barbed suture was a modified running stitch suturing technique with six suture crossing places along the incision [Figure 24].

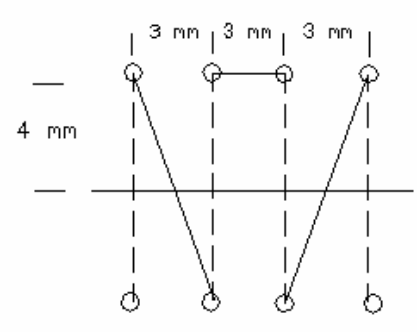

Figure 24. Modified running stitch suturing technique showing distances between bites and incision line.

The suturing technique for the monofilament polydioxanone control suture uses an interrupted stitch technique. There are three interrupted knotted stitches in the control model [Figure 25].

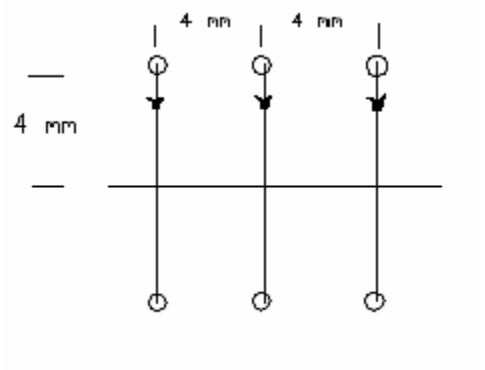

Figure 25. Interrupted stitch method showing distances between bites and incision line.

The stencils were traced onto the chamois leather to define the dog bone shape, the incision line, and the placement of bites for the specific suturing technique. The incision line was then cut in the middle of the dog bone shape specimen using a scalpel. The suturing technique was applied to approximate the wound edges and the specimen's outline was then cut out so that the two halves of the specimen were only held together by the sutures [Figure 23].

In order to measure the wound holding capacity the following equipment was required: MTS® model 1122 machine with a 250 lb. load cell and a rate of extension of 5.08 cm/min at a 5 cm gage length, Sony® Hi8 video recorder, a spotlight to provide adequate lighting, and image analysis system. The set-up required that the time to reach a 2 mm separation be recorded by the video camera. This time of test could be correlated with the load/cross head distance curve generated by the MTS mechanical tester set in tensile mode so as to determine the actual force at 2 mm separation, and the maximum load applied to achieve a 2 mm separation. The 2mm of separation could occur at any point along the incision line.

Modifications were made to the jaws (2 cm x 1.5 cm) of the MTS machine. The flat jaws of the MTS machine were modified, by applying sandpaper to the face of the jaws, to increase the frictional forces applied to the chamois leather so as to prevent slippage.

The Sony Hi8 video camera was mounted on a level tripod and placed at a fixed distance from the MTS machine. A spot light was used to create adequate lighting for viewing and video recording the experiment [Figure 26]. A ruler showing a metric scale

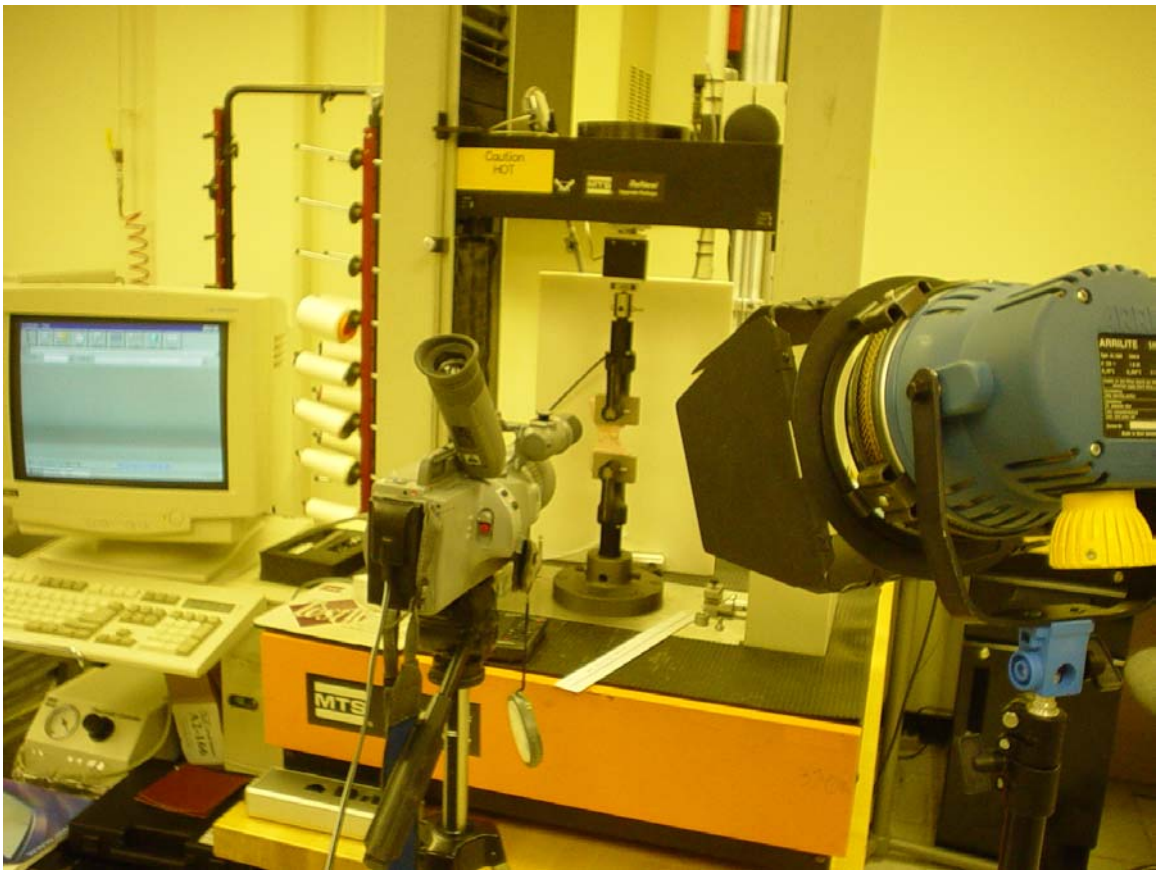

Figure 26. Picture showing wound holding capacity set-up.

was placed between the modified flat jaws. A short video of the ruler was recorded and used to calibrate the linear dimensions of the ruler tool of the image analysis system. The video camera was able to record a running time imbedded on the video tape. So by activating the MTS machine and the video record button simultaneously, the MTS machine and the video tape could be in synchronization. Each test was run until complete failure of the specimen, at which time the recording was stopped. Tests were performed on ten knotless barbed suture

specimens for each of the three lots with different cut angles and on ten polydioxanone monofilament control suture specimens.

Evaluation of the wound holding capacity was both time and load dependent. Video clips of the sample were captured by the image analysis system at one second intervals. The images were then analyzed using the image analysis system ruler tool set at a calibrated length of 2 mm. The first captured image that had a gap of 2 mm separation was recorded and the time imbedded on the video was noted as the time of failure. This time is then applied to the load/cross head distance graph saved in the MTS's computer. The y-coordinate of the graph was the load measured in pounds and the x-coordinate is crosshead distance in inches (Figure 27).

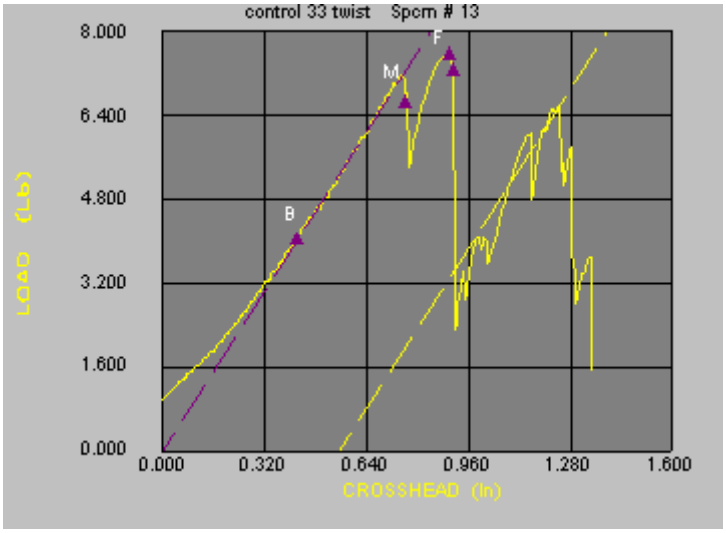

Figure 27. Graph showing a typical wound holding capacity test of pounds vs. crosshead distance

3.3.2 Method for Measuring Load Required to Give 2 mm Separation

By multiplying the rate of extension of 5.08 cm/min by the time to failure, the distance between clamps at the failure point was calculated and converted to the load at the time of failure. However, the load at failure was not always the maximum load experienced before

the 2 mm of separation. Therefore, both the load at 2 mm of separation and maximum load achieved before 2 mm of separation were recorded. Also recorded was the load required to completely cause the specimen to fail (this might have occurred after 2 mm of separation) and the type of rupture. The type of failure was classified as suture failure, knot slippage, or tissue simulant failure. The data was recorded in a Microsoft Excel spreadsheet. In the spreadsheet, the mean, standard deviation, and other descriptive statistics were calculated. One-way ANOVA was performed on the data, using $\alpha = 0.05$ in order to identify significant differences among the different types of sutures under test.

3.3.3 Method for Measuring Area of Separation at a Given Load

Another way to evaluate wound holding capacity of the knotless suture versus the monofilament control suture was to measure the area of separation at the incision line at a given load. This was accomplished by taking the load/cross head distance curve from the specimen tested and recording the time at which a specific load was reached. At this specified time, the area of separation at the incision line was evaluated using the image analysis system.

The specific load selected for the assessment was 11.12 N. This load was chosen because it corresponded to the minimum load required to achieve a 2 mm separation for all 4 types of sutures tested. This specific load was applied to the MTS graphs of wound holding capacity, and the crosshead distance and time to reach 11.12 N was recorded for each specimen. The video recorded image of the specimen at this calculated time was captured and its area of separation between the sutures was identified.

The image analysis system calculated the area of separation by the number of black pixels versus white pixels found in the captured image. The recorded colored image of the

specimen between the outside sutures was converted into a black and white image, and the area of separation was filled in with black pixels using the image analysis system's "pencil" tool. The rest of the image was then filled in with white pixels, and the image analysis system calculated the area of separation by counting the total number of black pixels in the captured image [Figure 28]. The data was recorded in a Microsoft

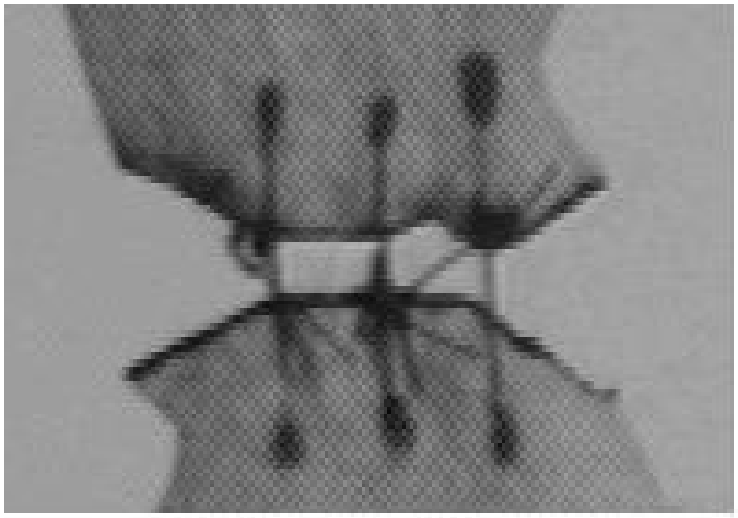

Figure 28. Manipulated image of typical wound holding capacity test specimen showing how area of separation at 11.12 N load was determined

Excel spreadsheet and the mean, standard deviation, and other descriptive statistics were calculated. One-way ANOVA was performed on the data, using $\alpha = 0.05$ in order to identify significant differences among the different types of sutures under test.

3.4 Statistical Analysis

Statistical analysis was conducted using an ANOVA test for testing significant differences between the three lots of knotless barbed sutures, the left and right sections of the barbed sutures, and the regions within the left and right sections with respect to the barb geometry. The ANOVA test was also used for testing significant differences between the three lots of knotless barbed sutures and the knotted control suture with respect to wound holding

capacity. The ANOVA test used an α value of 0.05 and the p-values were analyzed for significant differences within the statistical analysis test.

4. Results and Discussion

4.1 Characterization of Geometry Results

The experimental model of evaluating the knotless suture's barb geometry proved effective. The individual barb geometries of cut angle, cut depth, and cut length were successfully measured. The barb geometry of the L and R sections as well as the distances between cuts and number of cuts per unit length was successfully measured. The three lots of knotless barbed suture's geometries were successfully characterized and measured.

4.1.1 Results from 3 Lots of Barbed Sutures

Three specimens from each of the knotless barbed suture lots manufactured for this experiment were measured for cut angle, cut depth, cut length, distance between cuts, and number of cuts per unit length. The results determined that the three lots consisted of a low (1-SDB-6A), medium (1-SDB-5A), and high (1-SDB-5B) cut angle and cut length. The cut depth was inconsistent, yielding a low cut depth for lot 1-SDB-6A and higher cut depths for 1-SDB-5B and 1-SDB-5A. Tables 1, 2, and 3 show the mean barb geometry results calculated from 96 measurements taken on each of the three lots.

Table 1. Lot 1-SDB-6A barb geometries

Suture Geometric Parameter	Average ± Std. Dev.
Cut Angle (deg)	155.9 ± 2.0
Cut Depth (mm)	0.138 ± 0.019
Cut Length (mm)	0.339 ± 0.048
Distance B/W Cuts (mm)	0.941 ± 0.083
Number of cuts per length (6/mm)	6 per 5.60 ± 0.069

Table 2. Lot 1-SDB-5A barb geometries

Suture Geometric Parameter	Average ± Std. Dev.
Cut Angle (deg)	159.9 ± 2.1
Cut Depth (mm)	0.149 ± 0.030
Cut Length (mm)	0.438 ± 0.060
Distance B/W Cuts (mm)	0.938 ± 0.100
Number of cuts per length (6/mm)	6 per 5.64 ± 0.073

Table 3. Lot 1-SDB-5B barb geometries

Suture Geometric Parameter	Average ± Std. Dev.
Cut Angle (deg)	163.6 ± 2.1
Cut Depth (mm)	0.147 ± 0.029
Cut Length (mm)	0.518 ± 0.073
Distance B/W Cuts (mm)	0.949 ± 0.077
Number of cuts per length (6/mm)	6 per 5.65 ± 0.099

An ANOVA test was used to determine if there were any significant differences between the three lots of knotless barbed sutures [Appendix 1]. The p-values calculated [Table 4] from the ANOVA test showed that there were significant differences

Table 4. ANOVA test results showing p-values for testing significant difference between the 3 lots of sutures

Geometric Measurements	P-Value
Cut Angle	2.6E-76
Cut Depth	0.003
Cut Length	1.509E-57
Distance Between Cuts	0.89
Number of cuts per length	0.68

between the cut angle, cut depth, and cut length. However, no significant differences were found between the distance between cuts and the number of cuts per unit length.

4.1.2 Results of Left and Right Sections

The three lots were broken down into L and R sections containing four regions for each L and R section. The measurements for the L and R sections were averaged and the standard deviations were calculated for each parameter. Tables 5, 6, and 7 show the different barb geometries of the L and R sections measured from 48 observations taken from all 3 specimens in each of the three lots.

Table 5. Lot 1-SDB-6A barb geometries showing L and R sections

Geometric Measurement	Average ± Std. Dev.	
	L	R
Cut Angle (deg)	156.6 ± 2.0	155.2 ± 1.9
Cut Depth (mm)	0.136 ± 0.020	0.140 ± 0.020
Cut Length (mm)	0.343 ± 0.050	0.336 ± 0.040
Distance B/W Cuts (mm)	0.941 ± 0.080	0.941 ± 0.090
Number of cuts per length (mm)	6 per 5.62 ± 0.060	6 per 5.59 ± 0.080

Table 6. Lot 1-SDB-5A barb geometries showing L and R sections

Geometric Measurement	Average ± Std. Dev.	
	L	R
Cut Angle (deg)	160.1 ± 1.9	159.8 ± 2.2
Cut Depth (mm)	0.149 ± 0.020	0.152 ± 0.030
Cut Length (mm)	0.437 ± 0.060	0.438 ± 0.060
Distance B/W Cuts (mm)	0.943 ± 0.090	0.933 ± 0.110
Number of cuts per length (mm)	6 per 5.63 ± 0.070	6 per 5.67 ± 0.060

Table 7. Lot 1-SDB-5B barb geometries showing L and R sections

Geometric Measurement	Average ± Std. Dev.	
	L	R
Cut Angle (deg)	163.7 ± 1.9	163.6 ± 2.4
Cut Depth (mm)	0.145 ± 0.030	0.148 ± 0.030
Cut Length (mm)	0.505 ± 0.100	0.521 ± 0.080
Distance B/W Cuts (mm)	0.952 ± 0.060	0.946 ± 0.090
Number of cuts per length (mm)	6 per 5.66 ± 0.100	6 per 5.58 ± 0.100

An ANOVA test was used to determine if there were any significant differences between the L and R sections of the three lots of knotless barbed sutures [Table 8, Appendix 2].

Table 8. ANOVA test results showing p-values for testing significance between L and R sections

Geometric Measurement	1-SDB-6A P-value	1-SDB-5A P-value	1-SDB-5B P-value
Cut angle	0.0003	0.545	0.840
Cut depth	0.227	0.648	0.702
Cut length	0.467	0.935	0.813
Distance between cuts	0.980	0.710	0.770
Number of cuts per length	0.435	0.305	0.750

It was determined that Lots 1-SDB-5A and 1-SDB-5B did not have any significant differences between sections L and R. Furthermore, Lot 1-SDB-6A did not have any significant differences between its L and R sections for cut depth, cut length, distance

between cuts, and the number of cuts per unit length. However, Lot 1-SDB-6A did have a significant difference between the L and R sections in cut angle.

4.1.3 Results from Four Regions from Left and Right Sections

The four independent regions along the L and R sections of the knotless sutures were measured, by making 12 observations from the 3 specimens, and the averages and standard deviations were calculated as shown in Tables 9, 10, and 11.

Table 9. Table showing the regional differences between the L and R sections for suture 1-SDB-6A

Regional Means and Standard Deviations for Section L 1-SDB-6A				Regional Means and Standard Deviations for Section R 1-SDB-6A			
Regional	Cut Angle	Cut Depth	Cut Length	Regional	Cut Angle	Cut Depth	Cut Length
R1	156.0 ± 2.1	0.126 ± 0.013	0.311 ± 0.035	R1	155.1 ± 2.0	0.131 ± 0.015	0.311 ± 0.026
R2	156.8 ± 0.9	0.137 ± 0.012	0.348 ± 0.028	R2	155.3 ± 1.0	0.146 ± 0.012	0.349 ± 0.029
R3	156.2 ± 2.6	0.134 ± 0.015	0.334 ± 0.073	R3	154.7 ± 2.7	0.131 ± 0.015	0.311 ± 0.055
R4	157.4 ± 1.7	0.146 ± 0.015	0.378 ± 0.036	R4	155.4 ± 1.5	0.154 ± 0.015	0.37 ± 0.033

Table 10. Table showing the regional differences between the L and R sections for suture 1-SDB-5A

Regional Means and Standard Deviations for Section L 1-SDB-5A				Regional Means and Standard Deviations for Section R 1-SDB-5A			
Regional	Cut Angle	Cut Depth	Cut Length	Regional	Cut Angle	Cut Depth	Cut Length
R1	161.4 ± 1.3	0.122 ± 0.015	0.381 ± 0.042	R1	160.7 ± 1.7	0.122 ± 0.020	0.369 ± 0.036
R2	160.7 ± 0.1	0.147 ± 0.011	0.442 ± 0.023	R2	160.3 ± 1.9	0.149 ± 0.014	0.449 ± 0.025
R3	159.5 ± 2.4	0.148 ± 0.017	0.430 ± 0.069	R3	160.0 ± 2.0	0.148 ± 0.009	0.434 ± 0.039
R4	158.6 ± 1.5	0.180 ± 0.010	0.496 ± 0.032	R4	157.9 ± 2.2	0.188 ± 0.015	0.501 ± 0.029

Table 11. Table showing the regional differences between the L and R sections for suture 1-SDB-5B

Regional Means and Standard Deviations for Section L 1-SDB-5B				Regional Means and Standard Deviations for Section R 1-SDB-5B			
Regional	Cut Angle	Cut Depth	Cut Length	Regional	Cut Angle	Cut Depth	Cut Length
R1	164.7 ± 1.8	0.118 ± 0.019	0.445 ± 0.051	R1	165.3 ± 1.2	0.118 ± 0.024	0.464 ± 0.086
R2	164.4 ± 1.3	0.146 ± 0.017	0.543 ± 0.057	R2	164.2 ± 1.9	0.143 ± 0.020	0.528 ± 0.025
R3	163.7 ± 1.7	0.140 ± 0.015	0.497 ± 0.035	R3	163.2 ± 2.8	0.143 ± 0.022	0.499 ± 0.052
R4	162.0 ± 1.4	0.179 ± 0.014	0.579 ± 0.055	R4	161.7 ± 1.2	0.187 ± 0.013	0.597 ± 0.050

These results from the four regions show that some parameters of the barb geometry appear to change from the middle portion of the suture (Region 1) toward the needle end of the suture (Region 4). This is particularly noticeable for the cut depth and cut length which tend to increase from Region 1 to Region 4 [Figures 29 and 30].

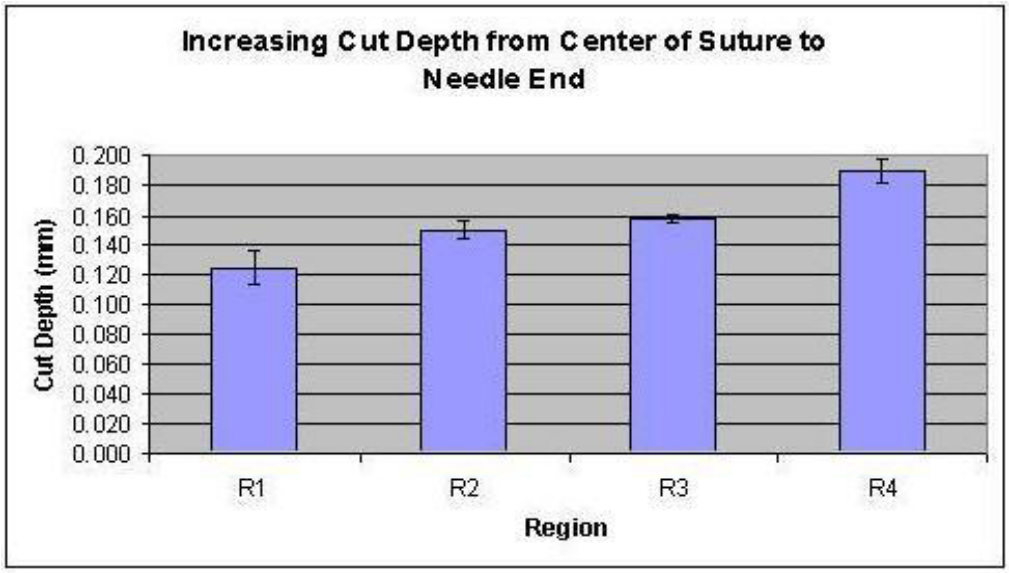

Figure 29. Cut depth of a typical knotless suture showing an increasing cut depth

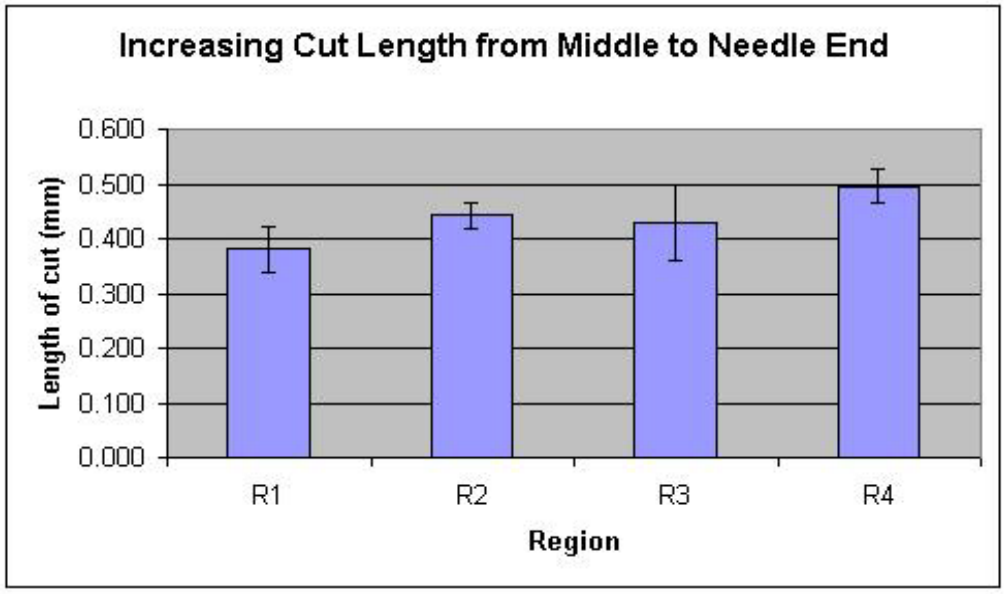

Figure 30. Cut length of a typical knotless suture showing an increasing cut length

The barb angles were analyzed statistically using an ANOVA test for measuring significant differences between the four regions on the L and R sections [Appendix 3]. The calculated p-values from the ANOVA test are shown in Table 12.

Table 12. ANOVA test showing p-values for testing significant differences between the four regions of the L and R sections

Geometric Measurement	1-SDB-6A		1-SDB-5A		1-SDB-5B	
	L	R	L	R	L	R
	P-value	P-value	P-value	P-value	P-value	P-value
Cut Angle	0.327	0.826	0.001	0.003	0.0005	0.0006
Cut Depth	0.107	0.001	4.58E-12	1.75E-12	3.31E-10	1.82E-09
Cut Length	0.009	0.001	2.31E-06	2.09E-11	3.76E-07	9.04E-06

Significant differences were found between the regions in the L and R sections of Lots 1-SDB-5A and 1-SDB-5B and between the regions of the R section for cut depth and both L and R sections for the cut length in Lot 1-SDB-6A. However, there were no significant differences between the regions of L and R sections for the cut angle of Lot 1-SDB-6A and in the L section for the cut depth of Lot 1-SDB-6A [Table 12].

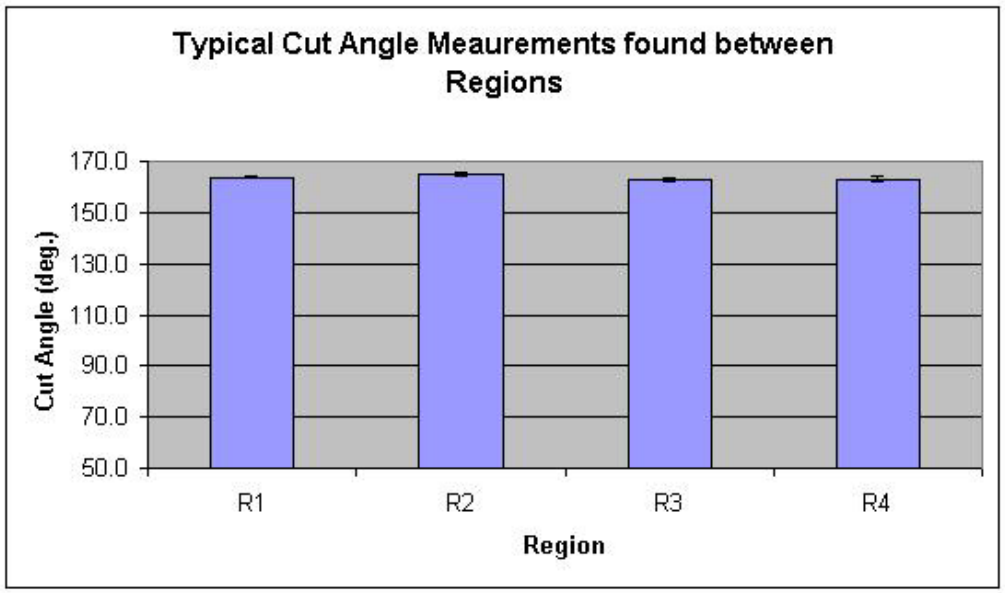

Figure 31. Cut angle measurements of a typical knotless suture showing no clear trends over the four regions.

This statistical analysis shows that there were mostly significant differences between the regions of L and R, further proving that there was an increasing trend in cut depth and cut length from the central region to the needle region.

The results confirm that the three lots received for testing contained different barb geometries when looking at the averages and standard deviations of the whole suture. As tests were conducted across all regions, differences and variability were observed. Though some variability occurred within the regions of measurement, it was unlikely that these irregularities affected the mechanical performance of the suture. Statistical analysis of the barb geometries proved helpful in determining significant differences between the lots being measured.

4.2 Wound Holding Capacity Results and Discussion

The two experimental models for evaluating surgical suture's wound holding capacity in an *in vitro* environment proved to be effective; the first in terms of evaluating the failure point at 2 mm of separation across the incision line, and the second in terms of evaluating the area of separation occurring at a specific load. Both experimental models gave definitive data to prove that the knotless barb suture maintained a superior tissue performance over the traditional equivalent knotted suture.

4.2.1 Wound Holding Capacity Evaluated at 2 mm of Separation

The wound holding capacity results show that the knotless barbed sutures appear to be superior to the equivalent conventional knotted suture in terms of the maximum load required to generate 2 mm of separation at the incision line [Figure 32].

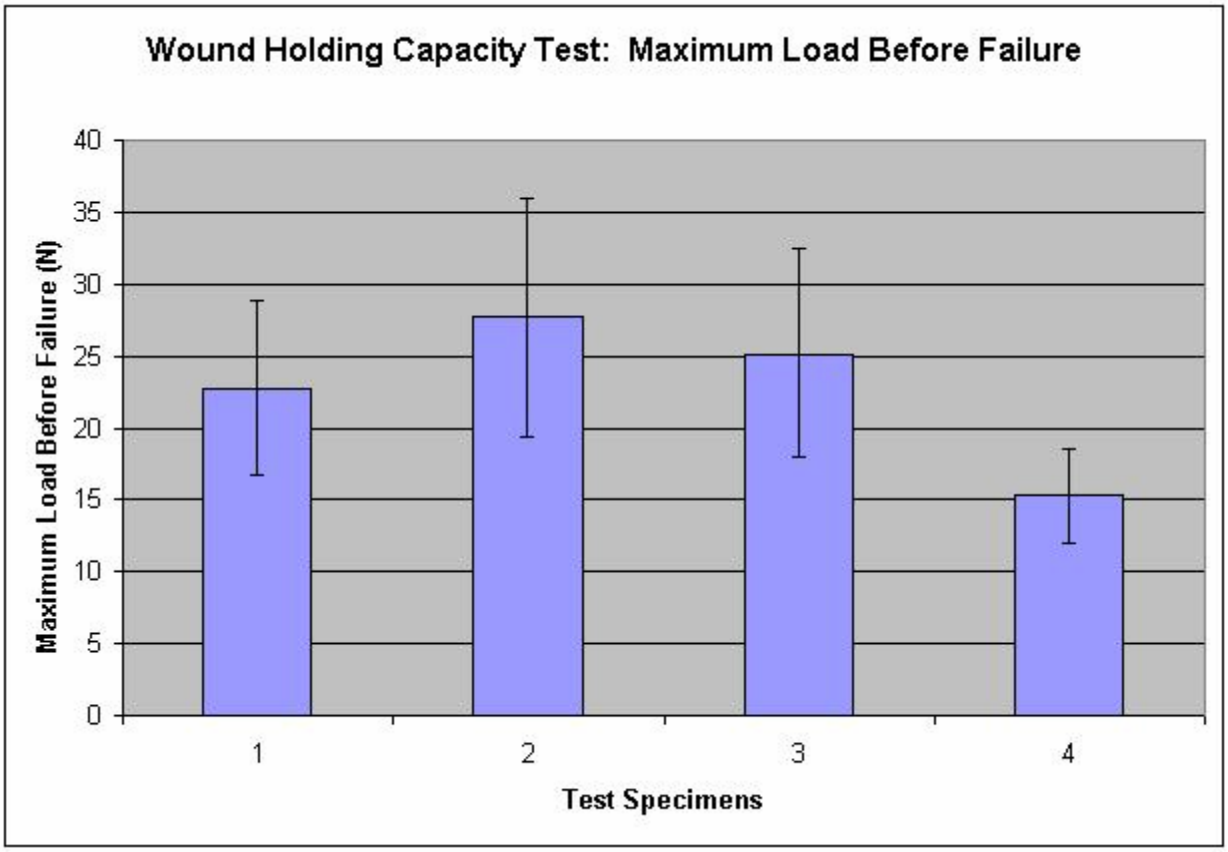

Figure 32. Graph showing wound holding capacity of knotless sutures versus the control suture in terms of the maximum load required to generate a 2 mm separation.

The averages and standard deviations of the results obtained from 10 specimens from each lot have been calculated and recorded in Table 13.

Table 13. Means and standard deviations of the wound holding capacity for knotless sutures versus control sutures occurring at 2mm of separation

Observations	1-SDB-5B	1-SDB-5A	1-SDB-6A	4-0 Control
	Mean ± Std. Dev.	Mean ± Std. Dev.	Mean ± Std. Dev.	Mean ± Std. Dev.
Time at failure (s)	24.8 ± 4.76	21.2 ± 4.44	29.2 ± 3.77	14.8 ± 2.68
Load at 2mm (N)	11.29 ± 7.83	15.91 ± 6.12	16.29 ± 6.98	14.34 ± 4.42
Max load before 2mm (N)	22.76 ± 6.14	27.72 ± 8.32	25.18 ± 7.32	15.25 ± 3.36

The maximum wound holding capacities evaluated at 2 mm of separation were analyzed statistically using an ANOVA test for measuring significant differences between the 4

different lots. The ANOVA test assumed an α value of 0.05, and the p-value results are shown in Table 14.

Table 14. ANOVA test results showing p-values for testing significance between the 4 lots of sutures

Observation	P-value
Load at 2mm	0.310
Max load before 2 mm	0.001

The results show that there were no significant differences between the 3 lots of barbed sutures and the 1 control suture lot when comparing the load measured at a 2 mm gap of separation. However, the ANOVA test results show also that there were significant differences when comparing the maximum load achieved before the 2 mm gap separation. The statistical analysis proves that the knotless barbed sutures withstood a higher maximum load before failure when compared to knotted monofilament control sutures using the specified stitching methods and chamois leather as a tissue simulant. This was due in part to the fact that the barbs of the knotless suture failed prior forming a 2 mm gap. As a result the tensile force required to make a 2 mm gap of separation [Figure 27] was lower than the maximum load during the test. The results in Tables 13 and 14 show that the maximum load that occurred before the 2 mm separation was higher for the barbed sutures than that of the control suture. This was likely due to the fact that the barbs interacted with the tissue throughout the length of the knotless barbed suture for wound closure. The monofilament control suture only interacted with the tissue at the bite points. This meant that limited frictional forces occurred between the monofilament suture and the tissue within the test specimen. High standard deviations occurred when testing the mechanical properties of the knotless barbed suture and the monofilament control suture because of the irregularities in the tissue simulant and variability in the applied suturing technique as mentioned previously in Chapter 1.

Another ANOVA test was conducted to test for significant differences between the 3 lots of knotless barbed sutures listed in Table 13. The results of the ANOVA are summarized in Table 15.

Table 15. ANOVA test results showing p-values for testing significant between the 3 lots of sutures

Observation	P-value
Load at 2 mm	0.23
Maximum load before 2 mm	0.33

The p-values listed in Table 15 show that there were no significant differences between the three barbed suture lots.

In addition to measuring the load required to form a gap of 2 mm at the incision line, the type of failure was observed. For the knotless barbed suture the type of failure that occurred for 28 out of the 30 specimens was barb failure [Figure 33]. For the other two specimens failure occurred due to tearing of the chamois leather and due to suture rupture. The monofilament control sutures all failed due to tearing of the chamois leather. The monofilament control suture did not fail due to knot slippage or suture rupture.

The type of failure can provide some understanding to how the knotless suture was reacting with the tissue under stress. For the knotless sutures because it was the individual barbs that failed, this suggests that the barbs were interacting with the tissue simulant. This also shows that the polydioxanone monofilament material was strong enough to transfer the applied barbs to the tissue under stress without suture rupture. However, the fact that the barbs "peeled" back [Figure 33] indicates that the bending and tearing behavior of individual barbs and the stress concentrations surrounding the barb site are the factors that control the ultimate failure of the knotless barb suture.

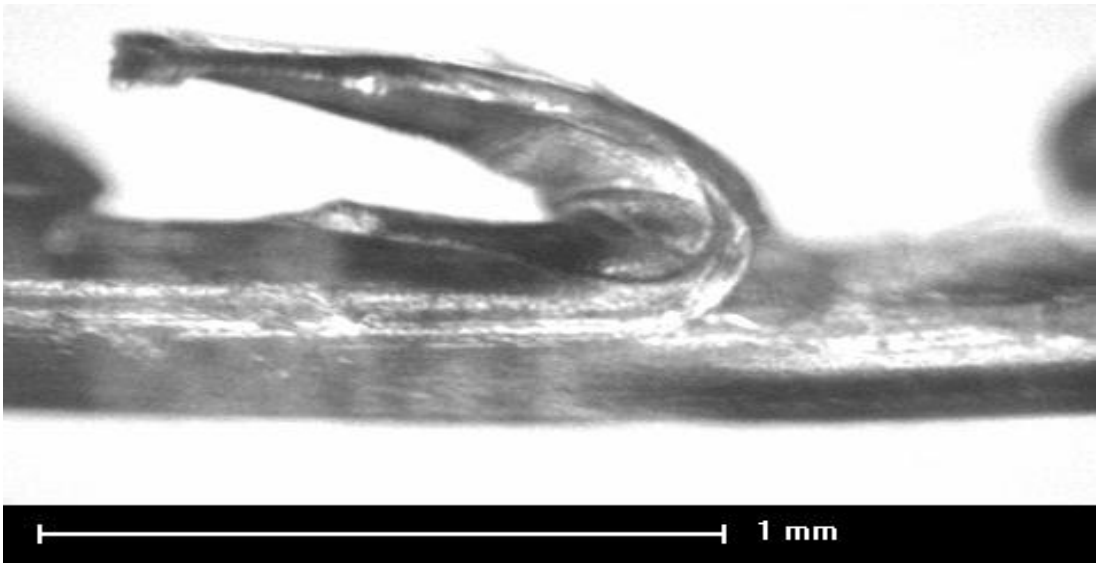

Figure 33. Suture extracted from test specimen after applied force showing individual barb failure

4.2.2 Wound Holding Capacity Evaluated as Area of Separation

The wound holding capacity of the knotless barbed sutures had superior wound holding characteristics compared to the knotted monofilament control suture when tested by the area of separation method as shown in Table 16. An area of separation occurred in only one of ten specimens in the knotless barbed suture Lot 1-SDB-5A, and in none of the other 20 specimens from Lots 1-SDB-5B and 1-SDB-6A. In comparison all 10 control specimens showed some area of tissue separation at the specific load of 11.12 N.

Table 16. Table showing means and standard deviations of the area of separation at 11.12 N for the knotless sutures and control sutures

Observations	1-SDB-5B	1-SDB-5A	1-SDB-6A	4-0 Control
	Mean ± Std. Dev.	Mean ± Std. Dev.	Mean ± Std. Dev.	Mean ± Std. Dev.
Area of Separation at 11.12 N(mm^2)	0.0 ± 0.0	0.167 ± 0.528	0.0 ± 0.0	3.382 ± 2.369

Table 16 clearly shows that the knotless barb sutures were able to maintain satisfactory approximation of tissue under a stress of 11.12 N whereas the monofilament control suture produced gaps in excess of the clinical failure criterion of 2 mm. This was due to the reasons explained previously. The barbs interacted with the tissue throughout the length of the

suture. The monofilament control suture only interacts with the tissue at the bite points which generated low frictional forces between the monofilament suture and the surrounding tissue simulant.

The area of separation was analyzed statistically using an ANOVA test for measuring significant differences between the four lots of sutures. The results are shown in Table 17.

Table 17. ANOVA p-value for wound holding capacity by the area of separation method

Observation	P-value
Area of Separation at 11.12 N	1.64E-07

The ANOVA test shows that there were significant differences between the knotless barbed suture and the knotted control suture when measuring the areas of separation.

.

5. Conclusions and Future Studies

5.1 Conclusion

This section describes whether or not the purpose and four objectives of the study as mentioned in Sections 1.3 and 1.4 have been met. With respect to Objective I, an experimental method has been found that gives reliable and consistent results when measuring the geometry of the barbed suture. The knotless barbed suture's geometry has been successfully classified and measured defining: 1) the whole suture 2) the left and right sections of the knotless barb suture, 2) the regional measurements of cut angle, cut depth, and the calculated cut length 4) the distance between cuts, and the number of cuts per unit length.

In answer to Objective II, an *in* vitro experimental method has been established that gives reliable measurements of the wound holding capacity when evaluating both the load required to form a 2 mm gap of tissue separation, and when measuring the area of separation at a given load. Using this *in vitro* experimental method for evaluating wound holding capacity determined that the knotless barbed suture gave a significantly higher maximum load before the 2 mm gap of separation occurred than that of the knotted monofilament control suture, when the specific stitching methods and a chamois leather tissue simulant were used. In addition, the *in vitro* experimental method for evaluating wound holding capacity it was determined that the knotless barbed suture gave a significantly smaller area of separation at a 11.12 N load that of the knotted control suture. The knotless barbed suture showed virtually no area of separation at the 11.12 N applied load. This successfully answers Objective III.

On reviewing the results of wound holding capacity to draw a conclusion for Objective IV, it was found in Table 13 that Lot 1-SDB-5A with the medium cut angle may have provided the highest maximum load before a 2 mm wound separation was reached.

However, it is shown in Table 15 that no significant differences in wound holding capacity were found between the 3 lots of barbed sutures with different cut angles. These results for the wound holding capacity indicate that the barb geometry of Lot 1-SDB-5A with a medium cut angle may be optimum geometry of the three lots, but this has not been demonstrated conclusively. Greater differences in the barb geometry between knotless barbed suture lots would be required to yield significant differences in wound holding capacity.

5.2 Future Studies

The knotless barbed sutures that have been manufacture so far do not necessarily have the optimum design of barb geometry. This study has provided useful information on how the barb geometry can be characterized and the wound holding capacity measured. This will assist the manufacturer in trying to find the ideal barb geometry that will give the best wound holding characteristics. Currently alternative barb designs are under consideration [Figures 34 and 35] and their wound holding performance needs to be evaluated..

Figure 34. New knotless barbed suture showing small distances between cuts

Figure 35. Knotless barbed suture showing large barbs

Future studies may find that the optimal barb geometry differs for the specific type of tissue that the barbs will be interacting with, i.e. fatty tissue, dermal layer, ligaments, and muscle tissue. It has been found in this study that the barbed suture fails at the barb site (Figure 33), so future studies need to characterize the bending behavior of the barbs as they interact with different types of tissue. It would also be advantageous to study other types of monofilament polymer sutures and how the application of barbs would affect their wound holding performance.

Future manufacturing capabilities may permit a systematic study by allowing certain barb geometry parameters to be fixed while others are changed, one parameter at a time. This would allow a wound holding capacity study to be conducted that would optimize the barb geometry parameter that yields the best results.

References

[1] Chu, CC, von Fraunhofer JA, and Greisler HP. Wound Closure Biomaterials and Devices. Boca Raton, FL: CRC Press, 1997.

[2] Kjaergard, HK. Suture support: Is it advantageous? *The American Journal of Surgery.* 2001; 182: 15S-20S.

[3] Black, JJ. A stitch in time – The history of sutures. *Nursing Times.* 1982 April 14-20; 78 (15): 619-23.

[4] Laufman, H, Rubel T. Collective Review. Synthetic Absorbable Sutures. *Surgery, Gynecology, and Obstetrics.* 1977 October; 145: 597-604.

[5] Frazza, EJ, Schmitt EE. A New Absorbable Suture. *Journal of Biomedial Materials Research Symposium.* 1971; 5(2): 43-58.

[6] Craig, PH. Williams JA, Davis KW, Magoun AD, Levy AJ, Bogdansky S, Jones, Jr JP. A Biologic Comparison of Polyglactin 910 and Polyglycolic Acid Synthetic Absorbable Sutures. *Surgery, Gynecology, and Obstetrics.* 1975 July; 141(1): 1-10.

[7] Moy, RL, Waldman B, Hein DW. A Review of Sutures and Suturing Techniques. *Journal of Demagogical Surgery and Oncology.* 1992 September; 18(9): 785-795. Review.

[8] Niessen, FB, Spauwen PHM, Kon M. The Role of Suture Material in Hypertrophic Scar Formation: Monocryl vs. Vicryl-rapide. *Annals of Plastic Surgery.* 1997 September; 39(3): 254-260.

[9] Ray, JA, Doddi N, Regula D, Williams JA, Melveger A. Polydioxanone (PDS), A novel monofilament synthetic absorbable suture. *Surgery, Gynecology, and Obstetrics.* 1981 October; 153(4): 497-507.

[10] Katz, AR, Mukherjee, DP, Kaganov, AL, Gordon S. A new synthetic monofilament absorbable suture made from polytrimethlyene carbonate. *Surgery, Gynecology, and Obstetrics.* 1985 September; 161(3): 213-222.

[11] McKee, GK. Metal anastomosis tubes in tendon suture. *The Lancet.* 1945 May 26: 659-660.

[12] Ruff, GL. Inserting device for a barbed tissue connector, US Patent 5,342,376; 1994 August 30.

[13] Ruff, GL. Barbed bodily tissue connector, US Patent 6,241,747 B1; 2001 June 5.

[14] Dattilo, Jr. PP, King MW, Cassill, NL, Leung JC. Medical Textiles: Application of an absorbable barbed bi-directional surgical suture. *Journal of Textile and Apparel, Technology and Management.* 2002 Spring; 2(2): 1-5.

[15] Alferness, CA. Cardiac disease treatment method. US Patent 6,085,754, 2000, July 11.

[16] Sadick, NS, D'Amelio, DL, Weinstein, C. The Modified Buried Vertical Mattress Suture. *Journal of Dermatologic Surgery and Oncology*. 1994 Nov; 20(11): 735-9.

[17] Motta, P, Erricheillo, C, Pontini, I. Achilles Tendon Rupture: A new technique for easy surgical repair and immediate movement of the ankle and foot. *The American Journal of Sports Medicine.* 1997 Mar-Apr; 25(2): 172-6.

[18] Dinsmore, RC. Understanding surgical knot security: A proposal to standardize the literature. *Journal of the American College of Surgeons.* 1995 Jun; 180(6): 689-99.

[19] Tera, H, Aberg, C. Strength of knots in surgery in relation to type of knot, type of suture material and dimension of suture thread. *Acta Chirurgica Scandinavica.* 1977; 143(2): 75-83.

[20] Trimbos, JB. Security of various knots commonly used in surgical practice. *Obstetrics and Gynecology*. 1984 August; 64(2): 274-280.

[21] Tera, H, Aberg, C. Tensile Strenths of twelve types of knots employed in surgery, using different suture materials. *Acta Chirurgica Scandinavica.* 1976; 142(1): 1-7.

[22] van Rijssel EJ, Brand R, Admiraal C, Smit I, Trimbos JB. Tissue reaction and surgical knots: the effect of suture size, knot configuration, and knot volume. *Obstetrics and Gynecology*. 1989 Jul; 74(1): 64-8.

[23] van Rijssel, EJC, Trimbos, JB, da Costa, A, Fleuren, GJ, Brand, R. Assessment of tissue reaction at suture knots; an adaptation of Sewell's scoring system. *European Journal of Obstetrics, Gynecology and Reproductive Biology.* 1988 Feb; 27(2): 165-72.

[24] Stoval, TG, Summitt, RL, Lipscomb, GH, Ling FW. Vaginal cuff closure at abdominal hysterectomy: Comparing sutures with absorbable staples. *Obstetrics and Gynecology.* 1991 Sep; 78(3 Pt 1): 415-8.

[25] Shapiro, AJ, Dinsmore, RC, North, Jr, JH. Tensile Strength of Wound Closure with Cyanoacrylate Glue. *The American Surgeon.* 2001 November; 67(11): 1113-5.

[26] Reiter, D. Methods and materials for wound management. *Otolaryngology of Head and Neck Surgery*. 1994 Jun; 110(6): 550-6. Review.

[27] Casha, AR, Yang, L, Kay, PH, Saleh, M, Cooper, GJ. A biomechanical study of median Sternotomy closure techniques. *European Journal of Cardio-thoracic Surgery.* 1999 Mar; 15(3): 365-9.

[28] Malina, M. Lindblad, B, Ivancev, K, Lindh, M, Malina, J, Brunkwall, J. Endovascular AAA Exclusion: Will stents with hooks and barbs prevent stent-graft migration? *Journal of Endovascular Surgery.* 1998 Nov; 5(4): 310-7.

[29] Conti JC, Strope ER. Evaluating the in situ loading and accelerated durability of barbs located on bifurcated aorto-iliac stent-grafts. *Biomedical Sciences Instrumentation*. 2000;36:93-8.

[30] Buncke, HJ. Surgical methods using one-way suture. US Patent 5,931,855; 1999 August 3.

[31] Duhaylongsod, FG. Anastomosis device and method. US Patent 6,241,741 B1; 2001 June 5.

[32] Alcamo, JH. Surgical suture. US Patent 3,123,077; 1964 March 3.

[33] Mansberger, AR, Jennings, ER, Smith, EP, Yeager, GH. A new type pull-out wire for tendon surgery: A preliminary report. *Bulletin of the School of Medicine, University of Maryland.* 1951; 36: 119-121.

[34] Bunnell, S. Gig pull-out suture for tendons. *The Journal of Bone and Joint Surgery.* 1954 July; 36-A(4): 850-1.

[35] McKenzie, A.R. An experimental multiple barbed suture for the long flexor tendons of the palm and fingers. Preliminary report. *Journal of Bone and Joint Surgery: British*. 1967 Aug; 49(3): 440-7.

[36] Leung, JC. Ruff, GL, Megaro, MA. Barbed, bi-directional medical suture: Biomechanical properties and wound closure efficacy study. *Society for Biomaterials: 28th Annual Meeting Transactions.* 2002 April; 25: 724.

[37] Tritle, NM, Haller, JR, Gray, SD. Aesthetic comparison of wound closure techniques in porcine model. *The Laryngoscope.* 2001 Nov; 111: 1949-1951.

[38] Buecheler, M. Din-orentierte festigkeitsprufung chirurgischer gewebeverbindungen. *Chirurg.* 1999 Mar; 70(3): 316-320.

Appendix 1

ANOVA Results for Testing Significant Differences

Between the Three Lots of Knotless Barbed Sutures

ANOVA Results for Testing Significant Differences between Lots For Cut Angle

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2896.8	2	1448.4	340.8	0.0	3.0
Within Groups	1211.1	285	4.2			
Total	4107.9	287				

ANOVA Results for Testing Significant Differences between Lots For Cut Depth

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.008	2	0.004	6.032	0.003	3.027
Within Groups	0.181	285	0.001			
Total	0.189	287				

ANOVA Results for Testing Significant Differences between Lots For Cut Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.559	2	0.779	214.411	1.50928E-57	3.027
Within Groups	1.036	285	0.004			
Total	2.595	287				

ANOVA Results for Testing Significant Differences between Lots For Distance between Cuts

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1	0.00	0.18	0.68	3.89
Within Groups	1.33	178	0.01			
Total	1.33	179				

ANOVA Results for Testing Significant Differences between Lots For Number of Cuts per Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1	0.00	0.02	0.89	4.03
Within Groups	0.35	52	0.01			
Total	0.35	53				

Appendix 2

ANOVA Results for Testing Significant Differences Between the L and R Sections of the Three Lots of Knotless Barbed Sutures

ANOVA Results for Testing Significant Differences between Sections L and R of Lot 1-SDB-5B

ANOVA Results for L and R Sections of Lot 1-SDB-5B for Cut Angle

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.2	1	0.2	0.0	0.8	3.9
Within Groups	420.2	94	4.5			
Total	420.4	95				

ANOVA Results for L and R Sections of Lot 1-SDB-5B for Cut Depth

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000	1	0.000	0.148	0.702	3.942
Within Groups	0.082	94	0.001			
Total	0.082	95				

ANOVA Results for L and R Sections of Lot 1-SDB-5B for Cut Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000	1	0.000	0.056	0.813	3.945
Within Groups	0.463	92	0.005			
Total	0.464	93				

ANOVA Results for L and R Sections of Lot 1-SDB-5B for Distance between Cuts

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1	0.00	0.09	0.77	4.01
Within Groups	0.35	58	0.01			
Total	0.35	59				

ANOVA Results for L and R Sections of Lot 1-SDB-5B for Number of Cuts per Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1	0.00	0.10	0.75	4.49
Within Groups	0.17	16	0.01			
Total	0.17	17				

ANOVA Results for Testing Significant Differences between Sections L and R of Lot 1-SDB-5A

ANOVA Results for Section L and R of Lot 1-SDB-5A for Cut Angle

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.6	1	1.6	0.4	0.5	3.9
Within Groups	401.3	94	4.3			
Total	402.9	95				

ANOVA Results for Section L and R of Lot 1-SDB-5A for Cut Depth

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000	1	0.000	0.209	0.648	3.942
Within Groups	0.065	94	0.001			
Total	0.065	95				

ANOVA Results for Section L and R of Lot 1-SDB-5A for Cut Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.301E-05	1	2.301E-05	0.007	0.935	3.942
Within Groups	3.218E-01	94	3.424E-03			
Total	3.218E-01	95				

ANOVA Results for Section L and R of Lot 1-SDB-5A for Distance between Cuts

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1	0.00	0.14	0.71	4.01
Within Groups	0.56	58	0.01			
Total	0.56	59				

ANOVA Results for Section L and R of Lot 1-SDB-5A for Number of Cuts per Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1	0.00	1.12	0.30	4.49
Within Groups	0.07	16	0.00			
Total	0.08	17				

ANOVA Results for Testing Significant Differences between Sections L and R of Lot 1-SDB-6A

ANOVA Results for Sections L and R of Lot 1-SDB-6A for Cut Angle

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	49.4	1	49.4	13.7	0.0004	3.9
Within Groups	338.4	94	3.6			
Total	387.8	95				

ANOVA Results for Sections L and R of Lot 1-SDB-6A for Cut Depth

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.001	1	0.001	1.477	0.227	3.942
Within Groups	0.034	94	0.000			
Total	0.034	95				

ANOVA Results for Sections L and R of Lot 1-SDB-6A for Cut Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.001	1	0.001	0.533	0.467	3.942
Within Groups	0.217	94	0.002			
Total	0.219	95				

ANOVA Results for Sections L and R of Lot 1-SDB-6A for Distance between Cuts

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6.67E-06	1	6.67E-06	0.00	0.98	4.01
Within Groups	0.41	58	0.01			
Total	0.41	59				

ANOVA Results for Sections L and R of Lot 1-SDB-6A for Number of Cuts per Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1	0.00	0.64	0.44	4.49
Within Groups	0.08	16	0.00			
Total	0.08	17				

Appendix 3

ANOVA Results for Testing Significant Differences Between Regions for the L and R Sections of the Three Lots of Knotless Barbed Sutures

ANOVA Results for Testing Significant Differences between Regions for Section L of Lot 1-SDB-5B

ANOVA Results of Regions for Section L of Lot 1-SDB-5B for Cut Angle

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	52.7	3	17.6	7.2	0.0005	2.8
Within Groups	107.3	44	2.4			
Total	160.1	47				

ANOVA Results of Regions for Section L of Lot 1-SDB-5B for Cut Depth

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.023	3	0.008	27.652	3.305E-10	2.816
Within Groups	0.012	44	0.000			
Total	0.035	47				

ANOVA Results of Regions for Section L of Lot 1-SDB-5B for Cut Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.122	3	0.041	15.921	3.759E-07	2.816
Within Groups	0.112	44	0.003			
Total	0.234	47				

ANOVA Results for Testing Significant Differences between Regions for Section R of Lot 1-SDB-5B

ANOVA Results from Regions of Section R from Lot 1-SDB-5B for Cut Angle

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	84.2	3	28.1	7.0	0.0006	2.8
Within Groups	176.0	44	4.0			
Total	260.1	47				

ANOVA Results from Regions of Section R from Lot 1-SDB-5B for Cut Depth

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.029	3	0.010	24.473	1.804E-09	2.816
Within Groups	0.018	44	0.000			
Total	0.047	47				

ANOVA Results from Regions of Section R from Lot 1-SDB-5B for Cut Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.116	3	0.039	11.716	9.041E-06	2.816
Within Groups	0.145	44	0.003			
Total	0.260	47				

ANOVA Results for Testing Significant Differences between Regions for Section L of Lot 1-SDB-5A

ANOVA Results for Regions of Section L of Lot 1-SDB-5A for Cut Angle

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	52.0	3	17.3	6.5	0.001	2.82
Within Groups	118.0	44	2.7			
Total	169.9	47				

ANOVA Results for Regions of Section L of Lot 1-SDB-5A for Cut Depth

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.021	3	0.007	36.839	4.576E-12	2.816
Within Groups	0.008	44	0.000			
Total	0.029	47				

ANOVA Results for Regions of Section L of Lot 1-SDB-5A for Cut Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.081	3	0.027	13.447	2.312E-06	2.816
Within Groups	0.088	44	0.002			
Total	0.169	47				

ANOVA Results for Testing Significant Differences between Regions for Section R of Lot 1-SDB-5A

ANOVA Results of Regions for Section R of Lot 1-SDB-5A for Cut Angle

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	61.5	3	20.5	5.3	0.003	2.8
Within Groups	169.9	44	3.9			
Total	231.3	47				

ANOVA Results of Regions for Section R of Lot 1-SDB-5A for Cut Depth

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.026	3	0.009	39.159	1.749E-12	2.816
Within Groups	0.010	44	0.000			
Total	0.036	47				

ANOVA Results of Regions for Section R of Lot 1-SDB-5A for Cut Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.106	3	0.035	33.374	2.088E-11	2.816
Within Groups	0.047	44	0.001			
Total	0.153	47				

ANOVA Results for Testing Significant Differences between Regions for Section L of Lot 1-SDB-6A

ANOVA Results for Regions of Section L for Lot 1-SDB-6A of Cut Angle

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	13.5	3	4.5	1.2	0.3	2.8
Within Groups	167.7	44	3.8			
Total	181.3	47				

ANOVA Results for Regions of Section L for Lot 1-SDB-6A of Cut Depth

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.003	3	0.001	2.152	0.107	2.816
Within Groups	0.017	44	0.000			
Total	0.020	47				

ANOVA Results for Regions of Section L for Lot 1-SDB-6A of Cut Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.029	3	0.010	4.409	0.009	2.816
Within Groups	0.095	44	0.002			
Total	0.124	47				

ANOVA Results for Testing Significant Differences between Regions for Section R of Lot 1-SDB-6A

ANOVA Results for Regions of Section R for Lot 1-SDB-6A of Cut Angle

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.1	3	1.0	0.3	0.8	2.8
Within Groups	154.0	44	3.5			
Total	157.2	47				

ANOVA Results for Regions of Section R for Lot 1-SDB-6A of Cut Depth

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.005	3	0.002	7.131	0.0005	2.816
Within Groups	0.009	44	0.000			
Total	0.014	47				

ANOVA Results for Regions of Section R for Lot 1-SDB-6A of Cut Length

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.031	3	0.010	7.233	0.0005	2.816
Within Groups	0.063	44	0.001			
Total	0.093	47				

Appendix 4

ANOVA Results for Testing Significant Differences in Wound Holding Capacity between the Different Suture Lots

ANOVA Results for Testing Significant Differences between the 4 Lots for the Load at 2 mm

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	155.08	3	51.69	1.24	0.31	2.87
Within Groups	1503.04	36	41.75			
Total	1658.12	39				

ANOVA Results for Testing Significant Differences between the 4 Lots for the Maximum Load bef

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	867.98	3	289.33	6.73	0.001	2.87
Within Groups	1547.27	36	42.98			
Total	2415.25	39				

ANOVA Results for Testing Significant Differences between the 3 Lots for the Load before 2 mm

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	154.89	2	77.45	1.58	0.23	3.35
Within Groups	1327.59	27	49.17			
Total	1482.48	29				

ANOVA Results for Testing Significant Differences between the 3 Lots for the Maximum Load bef

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	122.75	2	61.38	1.15	0.33	3.35
Within Groups	1445.89	27	53.55			
Total	1568.64	29				

ANOVA Results for Testing Significant Differences between the 4 Lots for Area of Separation at 1

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	83.17	3	27.72	18.82	1.643E-07	2.87
Within Groups	53.03	36	1.47			
Total	136.20	39				