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THE HEALING EQUINE LINEA ALBA

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BIOMECHANICAL INVESTIGATION OF THE HEALING EQUINE LINEA ALBA

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ABSTRACT

Biomechanical Investigation of the
Healing Equine Linea Alba

By

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Ventral midline incisional hernias in the horse following celiotomy may limit future use and require corrective surgery. To provide a better understanding of the biomechanics of wound healing of the equine abdominal wall, wound strength was quantitated in terms of ultimate load and energy absorbance in 30 ponies following celiotomy. The effects of duration of healing, wound location, and suture material type were determined by tensometry of the healing linea alba wound at seven-day intervals. Overall wound strength decreased in the first seven postoperative days, then increased rapidly during the next seven. Wound strength was equivalent to that of the normal linea alba by the 14th postoperative day, at which time it was also significantly stronger in the caudal abdominal wound compared to the cranial region. Wounds closed with gut suture were significantly stronger at the 28th postoperative day than those closed with polydioxanone sutures.

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"To save one from a mistake is a gift."

Herbert, 1965

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LIST OF ABBREVATIONS

EA	Energy absorbance (Failure energy)
IH	Incisional hernia
J	Joules
Kg	Kilogram
LA	Linea alba
mg	milligram
N	Newton
POD	Postoperative day
sem	Standard error of the mean
UL	Ultimate load (Breaking strength)

INTRODUCTION

The indications for gaining surgical access to the contents of the abdomen are many; in horses they include sudden anatomic displacement, ischemic diseases and impaction of the gastrointestinal tract, cesarean section in the mare, cryptorchidectomy, and cystotomy in males. In most cases the preferred approach to the abdomen is by celiotomy, or longitudinal incision of the linea alba, a tendinous union of the abdominal musculature and fascia, which comprises the ventral midline of the abdominal wall. A major complication in the horse of this approach is postoperative incisional hernia.

The number of cases of incisional hernia following celiotomy in horses is probably increasing, owing to an increase in the number of abdominal procedures performed. Incisional hernias may prevent use of the horse as an athlete, may increase the risk of gestation in brood mares, and constitute a serious cosmetic blemish. When compared to other domestic species, horses may be more at risk for developing incisional hernias, due to their propensity to rest in a standing position, the weight of their abdominal viscera, the relatively weak suture materials available for initial closure of the abdominal wall, and the increased proportion of procedures which result in or follow bacterial peritonitis.

A feature peculiar to equine incisional hernias is their late onset when compared to those occurring in humans and dogs. This point is difficult to support with hard evidence, but as a clinical impression most of these hernias seen in horses are first detected in the third and fourth post-operative weeks; in contrast to humans and dogs where they are usually noticed at the end of the first week. As the most commonly used absorbable suture materials have lost form 50% to 80% of their tensile strength between the second and third post-operative weeks, it is reasonable to wonder if there is a delayed wound healing sequence in the abdominal wall of horses that contributes to incisional hernia.

The hypothesis that horses have delayed wound healing of the linea alba was investigated. Ponies were used as an experimental model. The specific objectives of this study were: 1) To quantitate wound strength in the postoperative period, 2) to evaluate the influence of three different suture materials on wound strength of the linea alba in the postoperative period, and 3) to learn if there are differences of wound strength within the length of the incision.

REVIEW OF THE LITERATURE

"I do not think that, though much has been written thereon, it is yet adaquately recognized that the steps in making and in the repair of an abdominal wound are of the greatest importance."

Moynihan, 1926

Incisional Hernia

The presence of an incisional hernia (IH) is a significant cause of postoperative morbidity.(1) Most of what is known of this problem is to be found in the medical literature from retrospective studies of human patients requiring abdominal surgery. (2-4) A number of workers have described the incidence of these hernias, and have attempted to identify risk factors which predispose to their formation. Spies *et. al.* found 438 such hernias occurring in 34,300 people requiring abdominal incisions.(2) Bucknall's prospective evaluation of 1129 laparotomies revealed that 7.4% of these ended in IH.(5) A broad range is reported when rates of IH are examined: In one review IH were found to occurr in from 1.6% to 18.6% of human abdominal surgeries.(6) In general these variations may be accounted for by differences of detection method, case selection, and follow-up intervals.

Significant risk factors which have been associated with development of IH in humans include wound infection, male gender, ventral midline incisions made in the cranial abdomen, vertical incisions (those parallel to the linea alba), increasing age of the patient, obesity, postoperative cachexia, postoperative coughing, and diabetes.(2,7) One study also suggests that the longer the initial incision, the longer and wider will be the hernia which follows, should one occur.(2) There is recent awareness that IH may be first noticed long after surgery. As many as 50% of these hernias may develop more than a year after surgery, and there are several case reports describing initial onset from 6 to 12 years postoperatively. (2,7-9) Ellis found that late hernias, defined as those occurring more than one year after surgery, increase the IH rate by 5.8%, and that people in this late group did not have the accepted risk factors described above associated with onset of their hernias.(7) However, Harding found that of nine IH risk factors, only wound sepsis (in the perioperative period) was significantly associated with later hernias.(3)

Both in humans and canids, the majority of IH do occur, or at least are first detected, within the first two to four weeks following surgery.(10,11) The risk factors described for dogs are similar to those of humans including wound sepsis, advanced age, obesity, chronic cough, and poor surgical technique.(11)

The prevalence of this major complication of abdominal surgery has inspired many workers to search for better methods of treatment and prevention. Research efforts have concentrated on attempts to define the suture material, suture pattern, and suture tension which are best able to prevent IH.(12-19) Results of these studies are often in conflict, and usually not directly comparable with each other due to differences of experimental design. Preston *et. al.* may have best summarized the situation by stating:

> "A careless surgeon will have poor results by any method, and a good (careful) surgeon may have good results with poor methods."(20)

Review of the veterinary literature for information on IH in horses yields little data useful for comparison to other species. McIlwraith notes that "incisional hernias (in horses) may not be apparent in the immediate postoperative period, and tend to be noticed some time after surgery."(21)[a] Milne has stated that delayed

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[a] There is general agreement among a number of equine surgeons questioned on this point. The observation that such hernias occur late is a common anecdotal statement, but the literature is devoid of prospective studies which document this phenomenon. A review of four recent cases of incisional hernias from Michigan State University, Veterinary Clinical Center records reveals a mean time of detection on the 60th postoperative day, with a range of 29-90.

breakdown of the sutured abdominal wound may occur up to four months postoperatively.(22) There is also a broad range of suggestions relative to the safest suture material and suture pattern which should be used for closure of the equine abdominal wall.(21-25) In general, most authors suggest use of at least U.S.P. #2 size material, and interrupted suture patterns. When large incisional hernias must be repaired in horses, there is agreement by most equine surgeons that a prosthetic material is advantageous to cover the defect. Johnson describes the use of polypropylene mesh for successful repair of IH in ponies.(26) In an earlier project which employed wound tensometry, Allen compared the strength of different suture patterns in equine abdominal wounds. His conclusion was that a two-row imbricating continuous mattress suture pattern provided the greatest strength.(27)

Wound Healing

Wound healing in mammals may be considered a prolonged process; there are recognized tissue, cellular, and molecular events which herald the beginning of this process, but its ending depends very much on different objective points of view.(28) For example, the functional healing of an aseptic surgical skin incision may be considered complete in as little as eight days, when suture support is no longer required and epithelialization is complete. Yet there will be a number of changes observable in such a wound for at least another three months, and changes of wound strength may continue for a period of years.(30,31) The time-course of events in wound healing are also sufficiently different between different tissue types that comparisons should be based on similar tissues. Interspecies differences have been found between rates of healing for a given tissue type.(32)

Wound healing of connective tissue includes the descriptive lag, fibroplastic, and maturation phases.(29) These divisions describe physiologic events which occur over time, to produce functional scar tissue. In many wound healing studies, one accepted determinant of healing is the strength of the scar.(32) Accurate measurement of wound strength can be difficult, depending on the specific tissue or anatomic structure being evaluated. The majority of studies of tissue strength have examined skin or fascia with rodents as animal models.(33) With these models the qualitative features of increasing scar strength may be described, but there is little information detailing quantitative measurements for equids.(27)

The measured strength of collagenous tissue is influenced by a number of intrinsic and extrinsic factors. The intrinsic include collagen types and quantity present, age, hydration, elastin content, and numerous systemic aspects of general health and nutrition of the animal.(33) Reports of differing specific testing procedures suggest that rate of distension, orientation of the scar and normal collagen fibers, and the security of tissue-gripping clamps can produce wide variations of perceived strength of the wound tissue.(34) In a review of the literature which describes acquisition of strength by healing skin and tendons in several species, a number of statements emerge with which most authors would agree:

1) In the immediate postoperative period, the sutured skin or abdominal wall has 40% of its normal, unwounded strength.(35)

2) There is a measurable loss of wound strength in the first five to seven days.(35)

3) There is a rapid increase in wound strength from the seventh to the 21st day after wounding.(36)

4) The total healing time required for a scar to approach unwounded levels of strength varies with species, and is variable from one individual to the next.(36,37)

5) Scars in tendons never achieve the tensile strength of the normal, unwounded tissue being studied.(36)

6) Hollow abdominal viscera with a muscular wall may attain nearly 100% of normal strength in a relatively short time after wounding.(36

7) There is a prolonged period of gradual increase in wound strength after the fourth postoperative week, which may continue for longer that a year.(38)

8) Wound strength may be described in many ways; the best single method appears to be energy absorbance (EA).(39,40)[b]

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[b] When a material sample is tested to destruction by tensile forces, the area beneath a plot of load (in Newtons) against deformation (in meters) is the total energy absorbed by the sample (in Joules) on the way to mechanical failure.

The local biochemical events which accompany increasing wound strength reflect increasing content and molecular changes of collagen fibers.(41) There are histochemical and biomechanical difference between the fibrils of collagen Types I and III, which are the principle types found in healing wounds.(41)

The relative proportions of collagen fiber types found in a maturing scar change slowly with the age of a wound.(41) The replacement of the early appearing Type III collagen by the mechanically stronger Type I collagen as well as the appearance of elastin fibers, is part of the general process of the maturation phase of wound healing.(41,42) Increased organization of collagen fibers along lines of greatest local mechanical load, decreasing fiber solubility, and increased cross-linking within and between fibers probably continues for a period of months after a wound is visibly healed on its surface.(42-44)

The biomechanical events during healing of linea alba incisions have been described in rabbits and horses.(27,39,45) Important features of these studies include:

1) The normal unwounded linea alba in both species is stronger in tension than the sum of the anatomic layers which give rise to it (the adjacent abdominal wall).(27,39)

2) The measured strength of the linea alba will decrease as samples tested are gripped a greater distance away from the linea alba itself.(45)

3) Sutures contribute to wound strength up to the 14th postoperative day in rabbits.(35)

4) The strength of the immediate postoperative sutured linea alba is about 40% of the unwounded linea alba in rabbits, and varies from 31% to 86% in horses, depending on the suture pattern used.(27,35)

5) The cranial linea alba is weaker than its caudal region.(39)

Opinions vary with regard to the ideal site for abdominal incisions in humans. The goals of access to particular visceral structures, ease and security of closure, cosmesis, and prevention of incisional hernia combined with the changing cross-sectional anatomy of the several abdominal regions must all be considered. There is better agreement in the case of equine laparotomy: The ventral midline is preferred for most procedures.(21, 46,47) Only one description of the biomechanics of ventral midline celiotomy in horses was found in the veterinary literature.(27) This project was intended to show the strength and subsequent healing provided by different suture patterns and materials used in the abdominal wall. In Allen's work, the range of variation in healing time and the small number of samples within groups make interpretations difficult.(27) Also, the tensometry employed was the "bursting strength" class, which may be a source of error.(37) The major findings of this study are that a two-row imbricating continuous pattern of a multi-filament synthetic suture resulted in the best short and long-term wound strength.(27)

Surgeons have an interest in the effects of suture material type on the quality and strength of wound closure. Certainly there are other properties of suture materials to consider, but if one should fail to maintain tissue apposition through the early phases of wound healing, these other properties become of secondary importance. Two prospective studies evaluating different suture materials concluded that material type was not a deciding factor in the rates of wound sepsis and incisional hernia.(48,49) These trials did not attempt to describe actual wound strength with the different materials, and the small number of cases and short follow-up periods may have prevented showing significant differences. There has been a good deal of propriety work designed to quantitate changes in suture material strength over time, but few of these (as published) provide information on the strength of the wound itself.(50,56)

Wound Tensometry[c]

Quantitative measurement of the strength of tissues begins with an understanding of their behavior in tension

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[c] There are references in the biomechanics literature to tissue-tension measuring equipment, not always given the same generic name. In this thesis, the definitions found in Dorlands Medical Dictionary, 26th ed., 1981, and Webster's Third New International Dictionary, 1981, will be adhered to: Tensimeters measure the pressure of a gas or vapor, tensiometers measure the surface tension of a liquid, and tensometers measure the tension of a solid material.

and failure. When compared to materials such as glass and oil, tissue neither breaks nor flows. The term "viscoelastic" is applied to this third type of material response to load.(57) Collagenous structures including ligaments, fascia, and healing wounds all respond to progressive loading as shown in Figure 1.

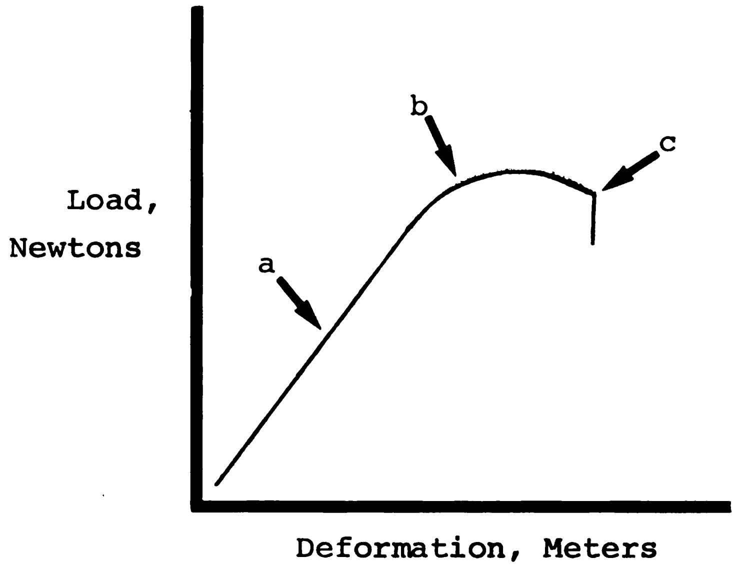

Figure 1. Viscoelastic load-deformation curve.

The overall shape of this curve reveals that a period of linear elongation (a), in response to loading is followed by plastic deformation (b), and ultimately failure (c). An overloaded tendon stretches, then tears, and finally breaks. As Evans and Barbenel note, the bulk of research has concentrated on the behavior of tissue in terms of sudden, forcible failure.(58) The biomechanics literature is devoid of studies of healing equine wounds which describes their behavior in terms of cyclic loading, as may be expected to occur *in vivo*. The complexity and cost of equipment to measure simple destructive failure of a material are considerably less than for equipment which uniformly loads and unloads a sample for thousands of cycles.

Nevertheless, the accepted standard of wound tensometry is sudden breakage and measurement of a momentary force sustained (ultimate load (UL), breaking strength, or very loosely, "tensile strength" or the energy absorbed by a tissue sample (wound) from the application of inexorable but constant displacement. The devices to produce such failure either require gross dissection of the the tissue to allow clamping to the jaws of a machine, or entrapment of the entire wound over a source of gas or fluid pressure to produce outward rupture. Each system has its advantages and disadvantages, and it may be helpful to list the requirements of the ideal wound testing apparatus.

1) The wound should be tested *in situ*, in normal position relative to surrounding tissues.

2) The wound should be kept alive, with its blood supply intact through testing.

3) Testing cycles should produce only normal (for the specific gross structure) force vectors, varying in scale or frequency instead of direction.

4) Testing equipment should be able to detect and announce the beginning of plastic deformation of tissue. This would provide an experimental endpoint without destructive testing.

5) The ability to accomplish testing in a sterile field might permit survival of the subject animal (probably anesthetized during testing).

Howes *et. al.* evaluated the strength of healing rectus abdominus muscle sheath in dogs by excision of wound samples and mounting them in a commercial Scott thread testing machine.(55) Botsford used two testing systems for determination of strength of guinea pig skin wounds.(59) The first was a simple screw mechanism that interposed a small spring scale between an attachment to one side of the skin wound and the traveler on a screw. The second (for stronger wounds) was a lever arm which was attached to the skin on one end and supported a small bucket of mercury on the other. A known amount of mercury was allowed to run into the bucket, and the force produced calculated from knowledge of the moment arms and density of mercury. This particular work is also interesting for being an early description of survival wound testing, though it seemed to produce a high standard error in the data (by today's standards). At the completion of testing an anesthetized subject, the wound was reclosed and the guinea pig allowed to recover. Wolarsky used a small box with the abdominal wall of rats fastened over an opening in one side.(60) Air was pumped into the box and pressure measured with a manometer, failure of the linea alba wound was recorded by an observer. Comparisons between samples were based on pressure to failure, and not in terms of linear tension.

Allen and Schannen adapted Wolarsky's method by using larger and stronger materials to permit testing of sutured linea alba from horses.(27,61) Cinematographic recording of the pressure on the air pump at the time of visible rupture of the abdominal wall was used to calculate the linear force perpendicular to the incision line. Peacock disputes the use of burst methods to calculate wound strength by showing that differences between radii of normal tissue and the healing tissue produce differing calculated failure force.(37) Even if the different radii are measured, the tension on the unstressed tissue section has not been. Abrahams used an early Instron Testor, which allowed cyclic force application to an excised tissue sample (but not a healing wound), with automated analog recording of load cell (strain gauge) voltages in connection with the time and sample displacement.(62) In this system, the specimen may be "cycled" while immersed in physiologic fluid, usually Ringer's solution.

The effects of sample storage until actual testing has been addressed by several workers. Viidik describes the alterations of tensile strength in rabbit cranial cruciate ligament after refrigeration, freezing, and formalin fixation.(63) Slight changes in one of five experimental variables studied followed storage by every method. The fact that some of the significant changes reflected increased tissue strength while others showed decreasing strength may be explained by the application of inappropriate statistical analysis (multiple iterations of Student's t-test within a group comparison, which would increase the likelihood of a false significant difference).

Viidik recommended that all mechanical testing of tissue should be done immediately after collection.(63) Matthews concluded that there was no significant change in the stress-strain curves of cat tendon after storage by freezing, although the elastic modulus did decrease after freezing.(64) He concluded that data in biomechanics should not be pooled from fresh and frozen samples. Woo *et. al.* looked at the effects of freezing rabbit ligaments at -20 degrees Celsius for three months and found that there were no changes in stress-strain behavior, but the frozen ligaments did have a lower ultimate load and modulus of elasticity.(65)

Suture Materials

Selection of suture size and material type is a judgement the surgeon makes at the time of surgery, and will be influenced by numerous factors of patient and procedure. In general, the size of a suture is described in the United States by an arbitrary number system which specifies the maximum and minimum diameter, and a minimum breaking strength for each number-size from ten-ought (10-0) up to number 7. These sizes and their equivalent metric sizes and diameters are listed in Appendix A. Exceptions include slight differences in diameter for gut suture, and the sizing of metallic wire is by Browne and Sharpe wire gauge.(66) The choice of suture size by the surgeon is based on a subjective estimate of the strength of the tissue to be apposed, the expected tension which must be supported by the suture line, and the principle that the foreign material remaining in a healing wound should be kept to a minimum.

The available combinations of chemical composition and physical form of suture materials provides a wide range of choice of sutures for a given application. Crane lists the currently manufactured materials, with their physical and surgical properties.(67) The physical properties of the ideal suture have been listed many times: Uniform diameter, high tensile strength, pliable, good knot security, low cost, and easily sterilized, to name but a few.(66) It should also evoke the least inflammatory, immunogenic, and carcinogenic tissue reaction, and not support sepsis.(67) The ideal suture material should also be absorbed at a constant rate after healing has progressed, or be encapsulated without complications.(67) Since no material yet devised has all these properties, and the materials available have differing combinations of these as well as a few undesirable properties, many workers have attempted to learn which product is most suitable for a given application.(19,50,52-54,56,68-77)

The anatomic structures which must heal following celiotomy or laparotomy are fibrous tendon or fascia, and may be expected to have slower rates of healing as measured by wound strength than skin or visceral tissue.(78) Sutures placed in the abdominal wall may also be exposed to accelerated degradation due to septic peritonitis. The specific requirements for a material used in closure of the linea alba of a horse include large size, high tensile strength, minimal tissue reactivity, persistence in the presence of septic peritonitis, and failure to promote the formation of fistulous suture tracts. McIlwraith suggests that polyglactin[d] is to be preferred over chromic gut for its greater strength; he also describes synthetic nonabsorbable monofilament material as acceptable.(21) While synthetic monofilament nonabsorbable materials are quite strong, they may promote formation of suture fistulae. Shires notes that recovery from anesthesia may be the most critical moment of the abdominal wall closure in horses.(47) He suggests that either absorbable or nonabsorbable sutures may be used, and prefers a simple interrupted pattern. Milne advocates the use of a large (U.S.P. #5) braided polyester material for closure of the ventral abdominal wall.(46) Huskamp reports that with the use of double strands of #2 polyglycolic acid[e] (PGA) in 790 procedures on horses, the rate of wound herniation was less than 1%, but duration of follow-up is not given.(79) Although the veterinary literature contains reports of problems with each material described, there appear to be fewer problems associated with monofilament nylon, polypropylene and

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d Vicryl - Ethicon, Somerville, NJ.

e Dexon - Davis and Geck, Manata, PR.

stainless steel. The polymers are criticized for poor knot security, and the wire suture for difficulty in handling.

There are a number of reports which describe the specific liability of different materials to produce a given adverse effect, including sepsis, decreased wound strength, and incisional hernia.(50,66,78,80) Edlich *et. al.* developed a model for contaminated suture material in mice. All material samples were treated with different dilutions of *Staphylococcus aureus* or *Escherichia coli* and the implanted suture strands and implant site evaluated on the fourth POD for signs of sepsis.(81) They found that there was significantly less infection associated with PGA suture material than with chromic gut, less with monofilament nylon and polypropylene than with stainless steel, and less with multifilament nylon than any other multifilament nonabsorbable material, including polyesters, silk, cotton, and stainless steel. Edlich's work led him to conclude that the chemical composition of a suture, and not its physical form, is the single most important property associated with infection. He also found that nylon and polypropylene consistently had the lowest infection rates, and that of the absorbable materials PGA was least prone to infection. He proposes that nylon and PGA have bacteriostatic degradation products to explain these findings, although this has only been shown *in vitro*.(81) Bucknall *et. al.* completed a series of experiments to show the relative *in vitro* adherence of *S. aureus* culture to different suture materials, and of the effect of suture/wound infections on wound strength of the incised linea alba of rats.(77) His findings include:

1) Braided silk will retain three times as many bacteria as monofilament nylon.

2) Braided nylon retains virtually the same number of bacteria as braided silk.

3) Braided PGA retains more bacteria than monofilament nylon, but less than braided silk.

4) There was no significant difference in wound strength between infected and uninfected wounds.

5) Bacteria were found by scanning electron microscopy between fibers of braided nylon and silk up to 70 days after implantation.

Bucknall concludes that synthetic nonabsorbable material should be used for closure of the abdominal wall. Barham found that PGA would result in stronger wounds in irradiated rabbit muscle fascia and in bladder wounds, and that there was less histologic reaction surrounding PGA when compared to chromic gut sutures.(68) Craig *et. al.* compared PGA and polyglactin (PGL) for material strength when implanted in rat gluteal muscle.(53) Their findings that PGL was stronger than PGA at all time intervals out to the 35th post-implantation day are consistent with another project which compared strength of the dry unimplanted materials.(51) Allen compared bursting strength of sutured equine linea alba, and found that a multifilament synthetic polyamide material was stronger than doubled strands of gut suture, but did not use comparable experimental groups.(27)

For this study, chromic gut, polyglactin, and polydioxanone sutures were used in a comparison of wound strength of the healing linea alba in ponies. Their chemical composition, physical structure, and characteristics and suture materials are described below.

Chromic gut is an absorbable, highly processed natural material. It may be obtained from the submucosa of sheep intestine, or the serosal layers of bovine intestine.(66) Sequential treatment with formaldehyde, cleaning solutions, and chromic salt solutions produce a soft, supple strand which must be stored in alcohol. While possessing excellent handling qualities, gut loses strength rapidly *in vivo*, and produces a severe foreign body reaction in the patient. To quote Crane: "[Chromic gut is] a traditional nonabsorbable (sic) that is being replaced by synthetic absorbable products in many practices."(67) The two features of this material which lessen its reliability in surgery are the unpredictable loss of strength which occurs both within an individual animal and between different species, and that knot security is poor.(66) Gut is recognized as likely to result in considerable fibrosis and scarring, due to its high tissue reactivity.

Polyglactin is a complex copolymer of glycolide and lactide.(82) Its chemical formula is $(C_2H_2O_2)_m(C_3H_4O_2)_n$

and the structural formula is shown in Figure 2.

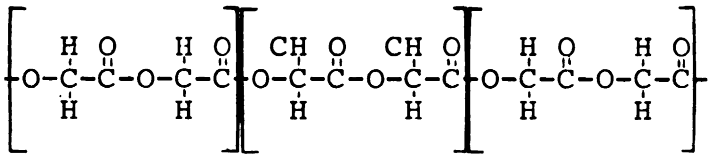

Figure 2. Structure of polyglactin.[f]

As surgical suture material it consists of a very fine continuous fibers braided into a somewhat stiff strand with high strength and good knot security. It is metabolized in the tissue by enzymatic hydrolysis at a constant rate. It retains 50% of its tensile strength at the 15th postoperative day, and is considered to be to be abrasive when drawn through the tissue being sutured. It is remarkably difficult to cut, at least in the larger sizes. Polyglactin also evokes minimal tissue reaction, and is completely absorbed by 90 days *in vivo*.(53)

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[f] From Craig, *et. al.*, Surgery, Gynecology, and Obstetrics, 1975; 141:1-10.

Polydioxanone (PDS) is a relatively new suture material which, like gut and PGL, is also absorbable. PDS differs in being a monofilament form, and has a chemical formula of $(C_4H_6O_3)_n$.(83) Its structural formula is shown in Figure 3.

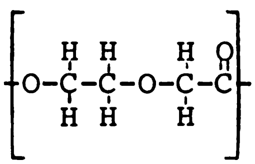

Figure 3. Structure of polydioxanone.[g]

Malnatii *et. al.* describe this material as having very low drag when drawn through tissues.(71) Ray *et. al.* suggest that this material is exceptionally strong, and retains its strength for a longer time than other absorbable materials.(84) PDS is hydrolyzed in a manner similar to PGL, but the process is less rapid due to its monofilament form. There is little early tissue reaction, and none seen by postoperative day 91.(84)

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[g] From Ray *et. al.*, Surgery, Gynecology and Obstetrics, 1981: 153:497-507.

MATERIALS AND METHODS

Experimental Animals and Groups

Thirty-six adult ponies were used in this project, equally divided between six experimental groups which were defined by duration of postoperative healing. Surgery was not performed on group one ponies which served as controls to provide strength of the normal linea alba; group two ponies were killed immediately after surgery, before wound healing could begin. Ponies in groups three, four, five, and six were maintained after surgery to allow normal wound healing to proceed for 7, 14, 21, and 28 days respectively. After a complete physical exam revealed no serious disease problems, ponies were preconditioned by vaccination for Eastern and Western equine encephalomyelitis, influenza, and for tetanus. Each was also treated with pyrantel pamoate at 6.6 mg/kg before being turned out to a 20 acre pasture for at least 30 days. All ponies were fed on pasture and provided access to salt blocks and water *ad libitum*. All ponies were identified by name and a numbered collar. Each was randomly assigned to one of the six experimental groups to distribute the variability which may have resulted from differences of age, weight, and gender. The signalment and grouping of ponies is described in Table 1.

Table 1. Signalment of experimental ponies.

Case No.	Name	No.	Age	Sex*	Weight**	Breed	Group
800131	Danny	93	2	m/c	195	Hackney	1
800123	Maria	98	12	f	177	Grade	1
800134	Mudd	92	2	f	134	Grade	1
800143	Wilma	55	4	f	211	Grade	1
800142	Toby	68	2	m/c	141	Grade	1
800129	Holly	72	20	f	145	Shetl.	1
800148	A-H	69	2	m/c	209	Hackney	2
800114	Barney	82	20	m/c	195	Grade	2
800118	Ginger	78	12	f	318	Grade	2
800146	Sarah	91	11	f	202	Grade	2
800138	Peggy	95	9	f	175	Grade	2
800147	Waldo	76	6	m/c	218	Grade	2
800113	Arlo	85	5	m/c	173	Grade	3
800076	Godmoth	56	16	f	255	Grade	3
800153	Grandpa	77	25	m/c	185	Grade	3
800137	Otto	83	9	m/c	193	Grade	3
800128	Daphne	96	14	f	173	Shetl.	3
800115	Wendy-O	83	17	f	177	Grade	3
800119	Floyd	62	2	m/c	193	Grade	4
800150	Norma	61	4	f	184	Grade	4
800139	Zelda	59	12	f	150	Shetl.	4
800152	Adolph	74	9	m/c	165	Grade	4
800151	Snuffy	70	15	m/c	213	Grade	4
800126	Blondie	86	4	f	184	Grade	4
800132	Katie	73	11	f	164	Shetl.	5
800015	Minerva	60	20	f	332	Grade	5
800135	Norma	67	12	m/c	164	Grade	5
800141	Pedro	97	16	m/c	191	Grade	5
800133	Marvin	64	10	m/c	184	Grade	5
800117	Delbar	75	2	m/c	145	Grade	5
800149	Vern	65	3	m/c	205	Hackney	6
800147	Reuben	57	4	m/c	175	Grade	6
800125	Mickey	89	2	m	184	Grade	6
800127	Beau	71	3	m	218	Hackney	6
800120	Gus	63	11	m/c	184	Shetl.	6
800121	Bonnie	80	2	m/c	164	Grade	6

* M - Male, F - Female, M/C - Gelding
** Weight in Kilograms

Description of Surgery and Postoperative Management

All ponies except those in group one were brought into a box stall in turn, and kept there for the day before and two days after surgery. Ponies were prepared on the day before surgery by clipping hair in a wide area over the ventral abdomen, from the xiphoid to the inguinal region. Each was given a single dose of procaine penicillin-G, at 22,000 iu/kg, and benzathine penicillin at the same dose by intramuscular injection three hours before induction of anesthesia. Ponies were given a single dose of five million i.u. sodium penicillin intravenously at the time of initial skin incision, and 4.4 mg/kg phenylbutazone intravenously at the completion of surgery. Feed was withheld for 12 hours prior to surgery. On the day of surgery each pony was prepared by grooming and introduction of a 14 gauge Teflon intravenous catheter.[h] Xylazine[i] was given as the preanesthetic sedation at 0.77 mg/kg intravenously, and a few minutes later induction of anesthesia accomplished with a fast intravenous drip of a mixture of 2 grams thiamylal sodium[j] in 500 ml of 10% guaifenesin, given to effect. Standard procedures for endotracheal intubation and maintenance on halothane anesthesia in a semi-closed system

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[h] Angiocath, Deseret Medical Inc., Sandy, Utah.

[i] Rompun, Mobay Corporation, Shawnee, Kansas.

[j] Bio-Tal, Bioceutic Co., St. Joseph, Missouri.

were used following induction. Ponies were positioned in dorsal recumbancy and the ventral abdomen prepared by scrubbing the skin with an iodophor scrub[k] preparation and with 70% propanol. Final skin preparation was with iodophor solution[l]. Standard methods of draping and aseptic procedures were used throughout surgery.

A 30cm sharp scalpel skin incision was made on the ventral midline and continued through the superficial fascia to expose the deep fascia of the external sheath of the rectus abdominus muscle. Hemorrhage of superficial vessels was controlled with electrocautery. The linea alba was divided with a scalpel for a distance of at least 27cm, craniad from the umbilicus. The length of the linea alba between the umbilicus and to a point five centimeters from the apex of the xiphoid cartilage was considered to have three regions of equal length, designated the cranial, middle, and caudal regions. Therefore, linea alba incisions were longer in larger ponies, to allow later comparison of wound strength by regions proportional to the size of the pony. The peritoneum was bluntly divided and the abdominal viscera then briefly explored in an attempt to locate major anatomic or physiologic disease processes, or pregnancy. Closure of the linea alba was accomplished using four

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[k] Betadine Surgical Scrub, Purdue Frederick Co., Norwalk, Connecticut.

[l] Betadine Solution, Purdue Frederick Co., Norwalk, Connecticut.

different suture materials in a simple interrupted pattern. All sutures were placed one centimeter from the cut margin of the linea alba and sutures were 1.5 cm apart. All sutures were U.S.P. #2 size swaged onto 3/8ths circle reverse cutting needles. Monofilament nylon was used for closure of the umbilicus, the cranial incision end, and wherever spacing sutures were required between regions. Polyglactin, medium chromic gut, and polydioxanone sutures were each used in turn, at least six simple interrupted sutures of a given material were used within a particular region before the next was begun. The sequence of placement for these three materials was alternated to ensure that each was present twice in each of the cranial, middle and caudal thirds of the incision, in each operated group of six ponies. This alternation within groups is shown in Figure 4. Two adjacent sutures of each of the three test materials were placed through a loop of 28 gauge stainless steel suture wire, the twisted ends of which were left in a subcutaneous pocket. This wire "tag" was placed to allow later identification of a suture material pair at the time of tissue segment dissection. Detail of suture placement is shown in Figure 5. At this point, the number, type, and relative position of all sutures placed in the abdominal wall were carefully identified and noted on a form by an assistant. Closure of the superficial layers proceeded using size 2/0 polypropylene[m] in a simple continuous pattern

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[m] Prolene, Ethicon Inc., Somerville, New Jersey.

in the subcutaneous tissue, and staples[n] for apposition of the skin. A dry sterile dressing was applied, and the wound bandaged with an adhesive elastic material.

Following recovery from anesthesia, each animal was bandaged with a heavy elastic bandage[o] which was removed on the seventh postoperative day (POD). Phenylbutazone[p] was given at 4.4 mg/kg per os every 12 hours beginning 12 hours after surgery for a total of 3 treatments. After the second POD, ponies were moved out into a sand lot for another five days, at which point those in groups with survival times longer than one week were returned to pasture.

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n Proximate II, Ethicon Inc., Somerville, New Jersey.

o Elastikon Elastic Tape, Johnson and Johnson, New Brunswick, New Jersey.

p Butazolidin Paste, Burrough Wellcome Co., Kansas City, Missouri.

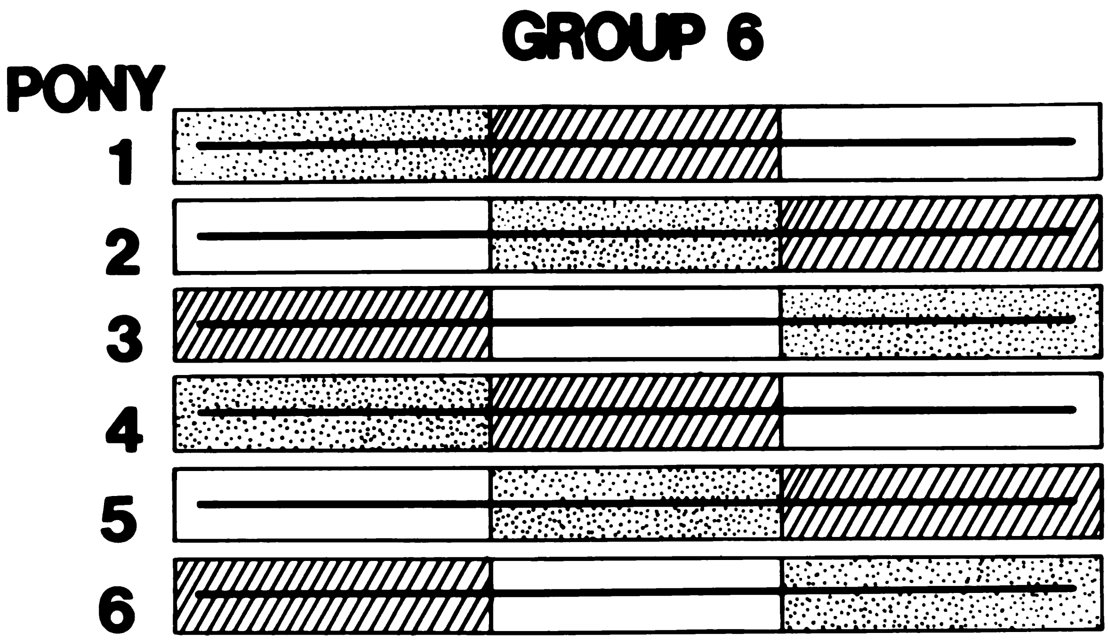
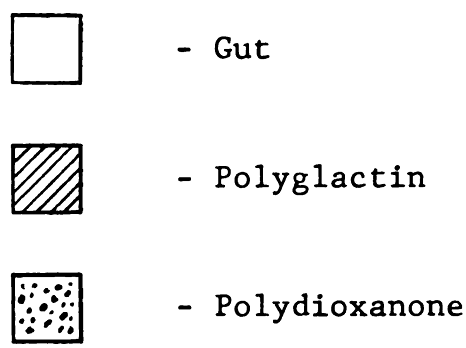


Figure 4. Rotation of suture material position using group six as an example. Each suture material type was present twice in each region of the incision within a group. The horizontal black lines represent the linea alba incision.



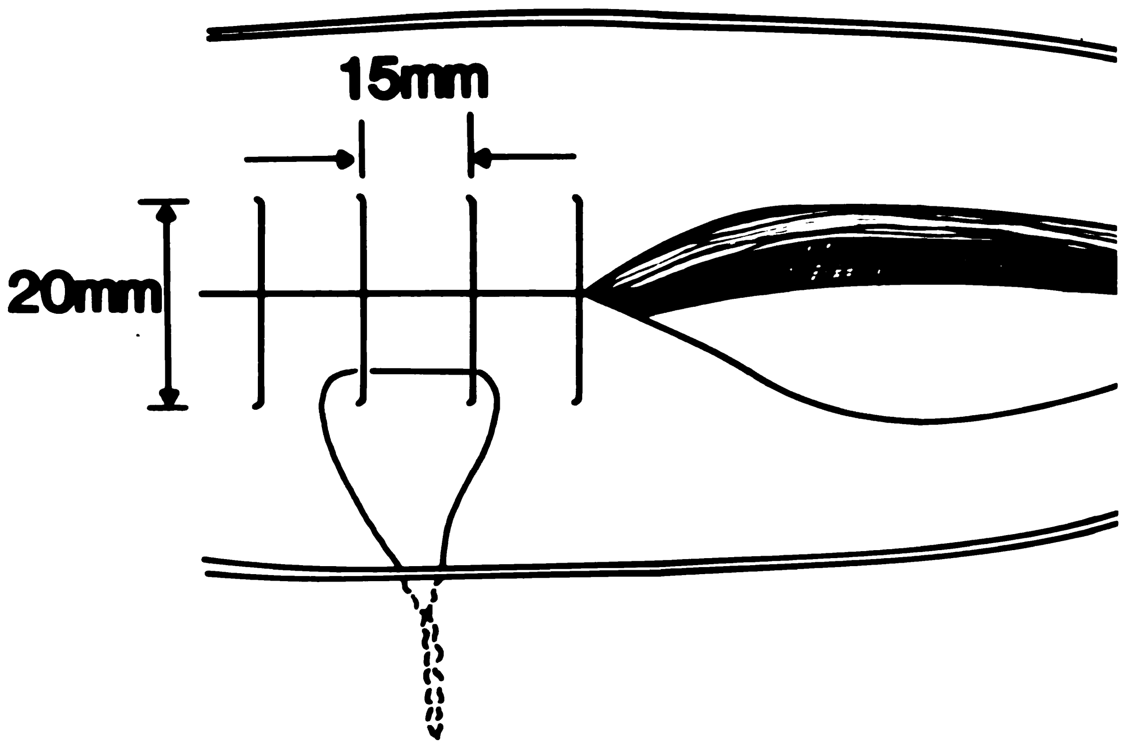


Figure 5. Detail of linea alba closure. The wire loop incorporating two adjacent sutures, one for each suture material type, is in the subcutaneous space.

Necropsy and Sample Collection

On the appropriate POD euthanasia was performed with intravenous pentobarbital sodium[q], given at 85 mg/kg. Necropsy began with removal of the skin covering the ventral abdomen. The gross appearance of the healing incision was noted, and a wide section of the full-thickness abdominal wall, with the sutured incision at its center was removed. The abdomen and its contents were then examined to identify gross signs of abnormal healing or adhesions. A plastic sheet marked with the pony's name, number, date of necropsy, and the orientation of the sample (cranial end) was applied to the 20 cm by 30 cm rectangular slab of the abdominal wall. The slab was placed in two heavy plastic bags, and immediately put in a flat position into a freezer at -60 degrees Celsius. Throughout the procedure of necropsy and sample storage, care was taken not to put undue tension on the healed linea alba.

Specimen Preparation and Mechanical Testing

The preparation and mechanical testing of the segments from all ponies was a batch process, and followed an average freezer storage time of 45 days. At this time the abdominal wall specimens were taken in random order to a dissection room adjacent to the testing area. The

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[q] Fatal-Plus, Vortech Pharmaceuticals, Dearborn, Michigan.

still-frozen abdominal wall was sectioned on a bandsaw to yield six, two-cm-wide sections of the incision line, each section containing two sutures of a given material type. Three of these sections also had one of the stainless steel wire loops present on the superficial surface. A numbered spring-clip was immediately applied to each section, for purposes of later identification. The six sections thus obtained from each pony were processed as a group, beginning with thawing in Ringers' lactated solution at room temperature. Each section was then dissected in a manner to discard the peritoneum, retroperitoneal fat, and rectus abdominus muscle, shown in Figure 6. This left a section 2 cm wide with an appearance similar to that shown in Figure 7. For sections which were to be tested without sutures, the pair of sutures were cut at this time.

Each section was tested in turn by the attachment of a grip system, loading into a servo-hydraulic mechanical testing device[r], and recording the force-deformation curve obtained. The grips employed for this project were prepared by bonding a carborundum grit cloth with epoxy cement to steel blocks, and clamping these with each side of the abdominal wall section in a "sandwich" (Figure 8), by means of adjustable locking pliers, as shown in Figure 9.

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[r] Instron Testor, Instron Corporation, Canton, Massachusetts.

The testing apparatus included the Instron testor, computer[s] and a videocamera and recording system.[t] After positioning the prepared specimen into the Instron testor, any slack in the tissue was removed by adjustment of the hydraulic ram, the sample was identified to the videocamera by a numbered card, and the computer-driven test program was initiated. The tissue section was distracted to failure at a constant rate of one cm/sec for a total distance of 5 centimeters. An example is shown in Figures 10 and 11. During this time a magnetic disk recorder recorded the time courses and force generated from a load-cell to which the section was attached and the motion of the hydraulic ram. These force and motion values were also displayed on an oscilloscope[u], the image of which was photographed at the completion of testing a tissue section. The vidoecamera recorded the visual appearance of wound distraction with a time signal initiated by the computer. At the completion of testing all tissue sections, the numerical data on magnetic disks was transferred to PDP 11/23 disk files for automated processing. The testing sequence and recording of data is depicted in a schematic shown in Appendix B.

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[s] PDP 11/23, Digital Equipment Corporation, West Concord, Massachusetts.

[t] Circon Color Microvideo Camera, Model MV9M330, Circon Corporation, Santa Barbara, California.

[u] Nicolet Oscilloscope, Nicolet Test Instruments, Madison Wisconsin.

Figure 6. Dissection of a wound segment. Prior to testing, the internal (i) and external (e) rectus sheath layers were isolated, and the peritoneum (p), retroperitoneal fat (f), and rectus muscle (m) were discarded. The scale on the right indicates centimeters.

Figure 7. Wound segment completely dissected. Only the internal and external rectus sheath, linea alba (arrow), and sutures remain.

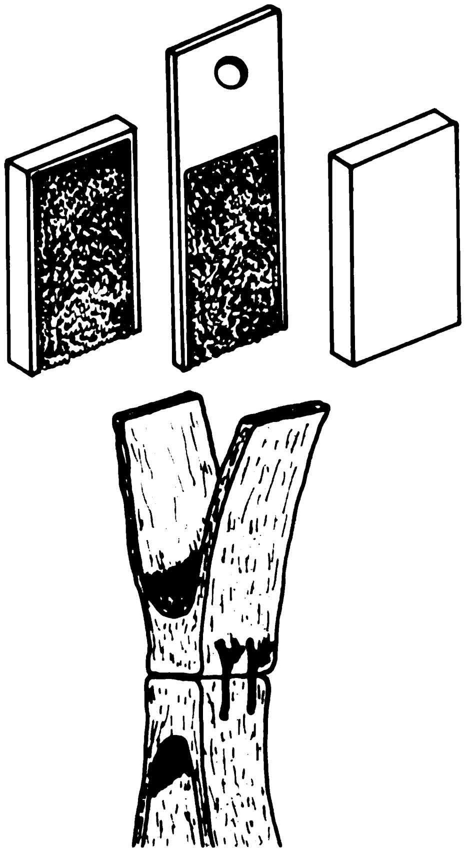

Figure 8. Design of tissue segment grips.

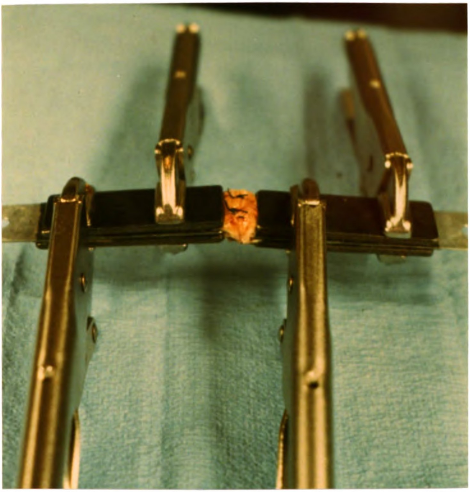

Figure 9. Wound segment with grips attached. Four locking pliers serve to grip tightly the grit-coated steel blocks and tissue "sandwich".

Data processing programs written at a later time enabled specific retrieval and printing of the values shown in Appendix C. The individual data points, obtained every 1/200 second, were plotted as load versus stroke curves by automated method. Videotape recordings of the testing procedure were reviewed at a later time to assess the location of section breaking (failure) and to learn if slipping of the tissue from the grips occurred.

For each experimental group the ultimate load (UL) and energy absorbance (EA) were compared against duration of postoperative healing, region of the abdomen, and suture material type.

Statistical Analysis

Multiple iterations of a computer-assisted block analysis of variance (ANOVA) were used to assess statistical significance[v]. The dependent variables for each of two procedures were either UL or EA, against the factors of healing time and region of the abdomen or suture material. Data was converted by log transformation prior to entry into the ANOVA program. The requirement for significance was a critical $p<0.05$.

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[v] Michigan State University Cyber 750 job numbers TB06320 and TB13238.

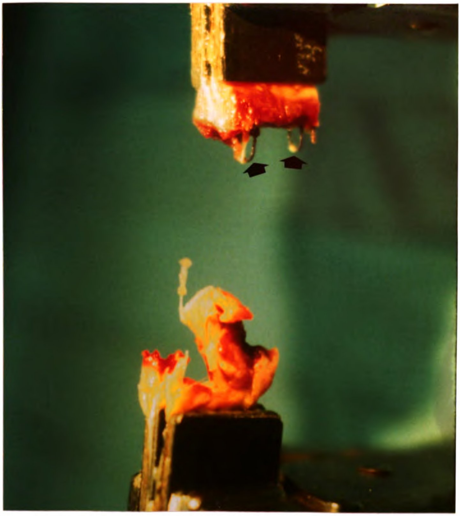

Figure 10. Distracted wound segment after failure. This section was from a group three pony; the two polyglactin sutures have not broken seven days after surgery (arrows).

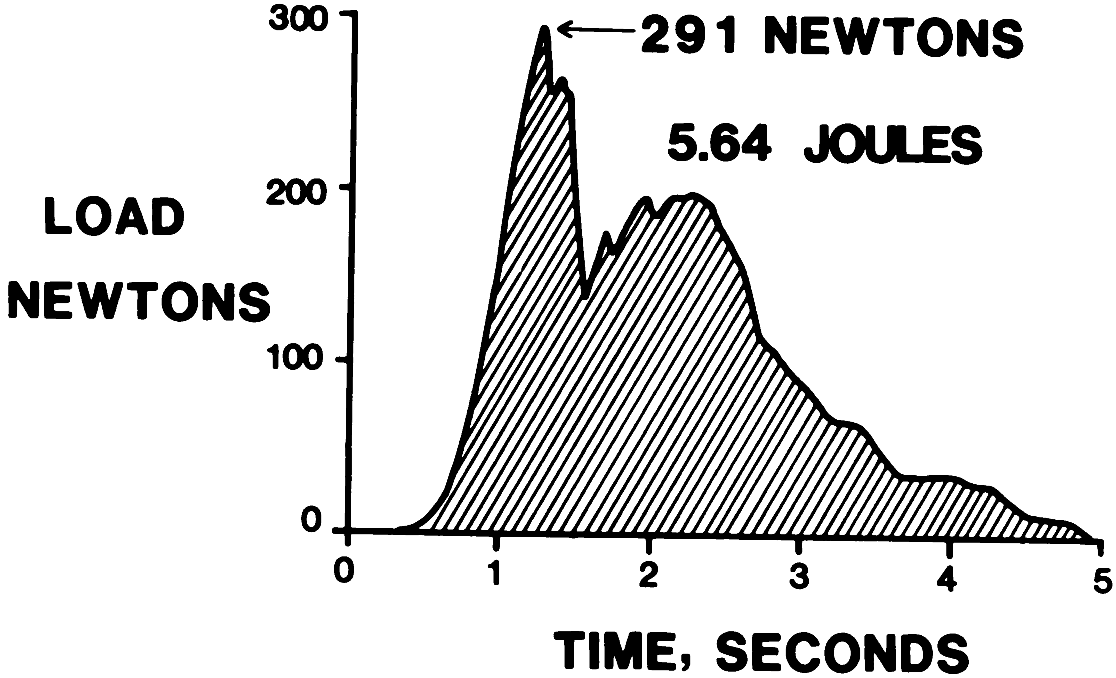

Figure 11. Example plot of load versus time. The ultimate load of a wound segment is the maximum force sustained, in Newtons (N). The energy absorbance is the total work performed to cause failure, and is the shaded area under this curve, if seconds of time are converted to meters of displacement, in units of Joules (J).

RESULTS AND DISCUSSION

"Tensile strength is the most important parameter of an incisional wound, both to the patient and to the surgeon."

Peacock, 1984

Data was lost due to recording failure at the time of testing for six of the 198 tissue sections studied. Data for these sections was reconstructed from the oscilloscope photographs and entered into the appropriate computer files manually. The numerical results of section testing for ultimate load in Newtons (N) and energy absorbance in Joules (J) are listed in Appendix C. The group means (x), standard deviations (sd), and standard errors of the mean (sem) are shown in Tables 2-9.

When wound strength in terms of UL is plotted against duration of healing (postoperative time) as shown in Figure 12, the overall sigmoid shape is apparent. This feature of wound strength dynamics was seen for all circumstances of UL and EA (Figure 13) regardless of suture material, region of the linea alba, or whether or not the sutures were present at the time of strength testing. When wound strength is evaluated in terms of energy absorbance the results are identical to those described for UL. The strength of the wound immediately following surgery and on

Table 2. Statistics of ultimate load for suture material groups, sutures removed, in Newtons.

	$\bar{X}$	sd	sem
GROUP: 1			
Vicryl			
PDS		n/a	
Gut			
All			
GROUP: 2			
Vicryl			
PDS		n/a	
Gut			
All			
GROUP: 3			
Vicryl	32	10	4
PDS	32	20	8
Gut	33	11	5
All	34	14	3
GROUP: 4			
Vicryl	215	54	22
PDS	256	88	36
Gut	205	53	22
All	225	67	16
GROUP: 5			
Vicryl	273	101	41
PDS	291	93	38
Gut	330	83	34
All	298	90	21
GROUP: 6			
Vicryl	345	117	48
PDS	369	182	74
Gut	340	68	28
All	351	124	29

Table 3. Statistics of ultimate load for suture material groups, sutures intact, in Newtons.

	$\overline{X}$	sd	sem
GROUP: 1			
Vicryl			
PDS		n/a	
Gut			
All			
GROUP: 2			
Vicryl	108	34	14
PDS	97	54	22
Gut	92	27	11
All	99	38	9
GROUP: 3			
Vicryl	113	46	21
PDS	92	33	14
Gut	52	34	14
All	84	44	11
GROUP: 4			
Vicryl	264	106	43
PDS	260	70	29
Gut	269	64	26
All	264	77	18
GROUP: 5			
Vicryl	334	104	42
PDS	298	60	24
Gut	312	56	23
All	315	74	17
GROUP: 6			
Vicryl	325	139	57
PDS	362	165	68
Gut	336	102	42
All	341	131	31

Table 4. Statistics of ultimate load for incision region groups, sutures removed, in Newtons.

	$\overline{X}$	sd	sem
GROUP: 1			
Region 1	226	98	40
2	301	92	37
3	278	94	38
Total	269	91	22
GROUP: 2			
Region 1			
2		n/a	
3			
Total			
GROUP: 3			
Region 1	33	13	5
2	35	12	5
3	34	20	9
Total	34	14	3
GROUP: 4			
Region 1	283	65	27
2	197	58	23
3	195	39	16
Total	225	67	16
GROUP: 5			
Region 1	295	109	44
2	341	104	42
3	259	34	14
Total	298	90	21
GROUP: 6			
Region 1	463	107	44
2	307	111	46
3	283	71	29
Total	351	124	29

Table 5. Statistics of ultimate load for incision region groups, sutures intact, in Newtons.

	$\overline{X}$	sd	sem
GROUP: 1			
Region 1	198	67	27
2	299	94	39
3	278	94	38
Total	258	92	22
GROUP: 2			
Region 1	120	54	22
2	93	26	11
3	84	23	9
Total	99	38	9
GROUP: 3			
Region 1	104	53	22
2	84	35	14
3	59	37	17
Total	84	44	11
GROUP: 4			
Region 1	327	47	19
2	259	88	36
3	207	40	16
Total	264	77	18
GROUP: 5			
Region 1	279	66	27
2	337	84	34
3	329	67	27
Total	315	74	17
GROUP: 6			
Region 1	343	198	81
2	362	97	39
3	318	91	37
Total	341	131	31

Table 6. Statistics of energy absorbance for suture material groups, sutures removed, in Joules.

	$\overline{X}$	sd	sem
GROUP: 1			
Vicryl			
PDS		n/a	
Gut			
All			
GROUP: 2			
Vicryl			
PDS		n/a	
Gut			
All			
GROUP: 3			
Vicryl	0.4	0.2	0.1
PDS	0.3	0.2	0.1
Gut	0.3	0.1	0.1
All	0.3	0.2	0.1
GROUP: 4			
Vicryl	2.6	0.5	0.2
PDS	3.0	1.2	0.5
Gut	2.6	1.2	0.5
All	2.7	1.0	0.2
GROUP: 5			
Vicryl	3.3	1.4	0.6
PDS	3.1	0.5	0.2
Gut	4.1	0.7	0.3
All	3.5	1.0	0.2
GROUP: 6			
Vicryl	4.6	1.1	0.4
PDS	5.9	3.6	1.5
Gut 4.9	1.8	0.7	
All	5.1	2.4	0.6

Table 7 Statistics of energy absorbance for suture material groups, sutures intact, in Joules.

	$\overline{X}$	sd	sem
GROUP: 1			
Vicryl			
PDS		n/a	
Gut			
All			
GROUP: 2			
Vicryl	1.2	0.4	0.2
PDS	1.3	0.6	0.3
Gut	1.0	0.5	0.2
All	1.3	0.5	0.1
GROUP: 3			
Vicryl	1.6	1.1	0.4
PDS	1.3	0.5	0.2
Gut	0.6	0.6	0.2
All	1.2	0.8	0.2
GROUP: 4			
Vicryl	3.0	1.1	0.4
PDS	3.0	0.7	0.3
Gut	3.2	1.1	0.4
All	3.0	0.9	0.2
GROUP: 5			
Vicryl	4.1	1.3	0.5
PDS	3.3	1.1	0.5
Gut	4.2	0.8	0.3
All	3.9	1.1	0.3
GROUP: 6			
Vicryl	4.9	2.5	1.0
PDS	4.7	1.6	0.6
Gut	4.5	1.8	0.7
All	4.7	1.9	0.5

Table 8 Statistics of energy absorbance for incision region groups, sutures removed, in Joules.

	$\bar{X}$	sd	sem
GROUP: 1			
Region 1	2.9	1.0	0.4
2	3.9	2.3	0.9
3	3.6	1.3	0.5
Total	3.5	1.6	0.4
GROUP: 2			
Region 1			
2		n/a	
3			
Total			
GROUP: 3			
Region 1	0.3	0.2	0.1
2	0.3	0.2	0.1
3	0.3	0.2	0.1
Total	0.3	0.2	0.1
GROUP: 4			
Region 1	3.2	0.9	0.4
2	2.9	1.0	0.4
3	2.0	0.8	0.3
Total	2.7	1.0	0.2
GROUP: 5			
Region 1	2.8	0.9	0.4
2	4.1	0.9	0.4
3	3.5	0.9	0.4
Total	3.5	1.0	0.2
GROUP: 6			
Region 1	5.9	2.9	1.2
2	4.3	2.6	1.1
3	5.2	1.3	0.5
Total	5.1	2.4	0.6

Table 9 Statistics of energy absorbance for incision region groups, sutures intact, in Joules.

	$\bar{X}$	sd	sem
GROUP: 1			
Region 1	3.2	1.1	0.5
2	3.9	2.3	0.9
3	3.0	0.9	0.3
Total	3.4	1.5	0.4
GROUP: 2			
Region 1	1.2	0.5	0.2
2	1.3	0.5	0.2
3	1.3	0.5	0.2
Total	1.3	0.5	0.1
GROUP: 3			
Region 1	1.6	1.2	0.5
2	1.0	0.6	0.3
3	0.9	0.4	0.1
Total	1.2	0.8	0.2
GROUP: 4			
Region 1	3.6	1.0	0.4
2	3.1	0.8	0.3
3	2.5	0.8	0.3
Total	3.0	0.9	0.2
GROUP: 5			
Region 1	3.8	0.9	0.4
2	3.9	1.4	0.6
3	3.9	1.4	0.6
Total	3.9	1.1	0.3
GROUP: 6			
Region 1	4.2	2.2	0.9
2	5.5	2.0	0.8
3	4.4	1.4	0.6
Total	4.7	1.9	0.5

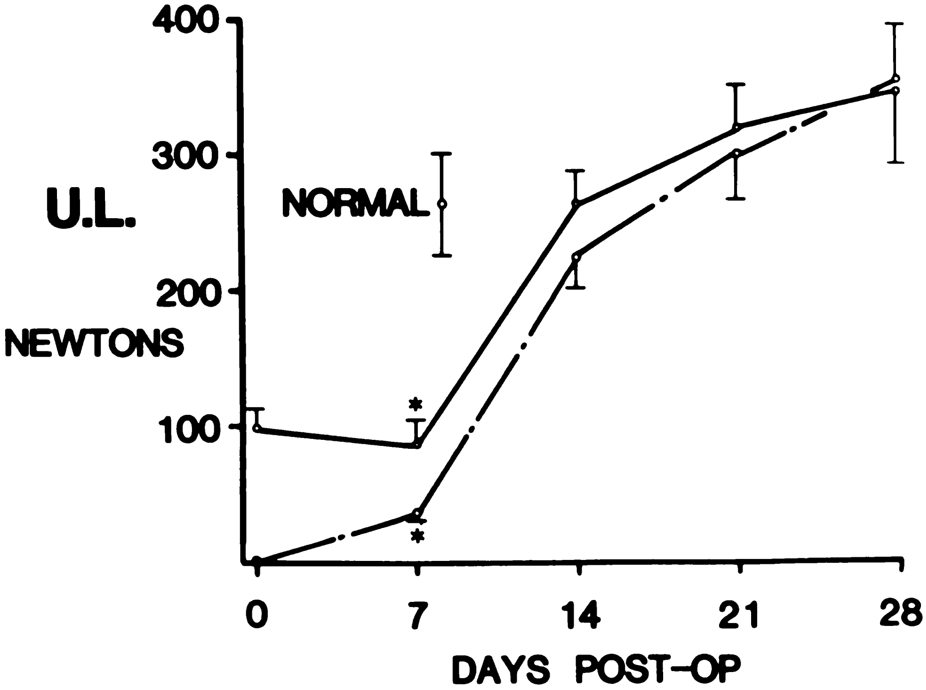

Figure 12. Ultimate load of wounds as a function of postoperative time. The solid line (o———o) represents strength of the wound with sutures intact. The broken line (o—-—o) shows strength of wounds from which the sutures were removed. Error bars are equal to one standard error of the mean, and those with asterisks have group means significantly different from the other means at the same postoperative time.

postoperative day seven was significantly different (lower) than wound strength on the 14th, 21st, and 28th postoperative day. The stength of the linea alba with sutures was significantly greater than the same wound without sutures on the day of surgery and on the seventh POD. From the 14th postoperative day through to the 28th, wound strength with or without suture support is not significantly different from that of the normal linea alba by either strength variable (UL or EA). There is a trend of wound strength exceeding that of the unwounded structure, but at the experimental endpoint of 28 days healing, this difference was not significant. It is interesting to note that for both variables the strength of the wound without sutures becomes stronger when compared to the wound with sutures between the 21st and 28th postoperative day, although the difference is not significant. There are two likely explanations for this finding: First, that dissection of the individual tissue sections to a depth necessary to cut the embedded sutures may have weakened the fibrous wound, or second, that the vertical penetration of adjacent fascia and bridging of the wound by suture material was a site of stress concentration, which allowed distraction forces to act on collagen fiber orientation in an unfavorable direction.

The overall time effects of equine linea alba healing are similar to those shown by other species. Peacock states that:

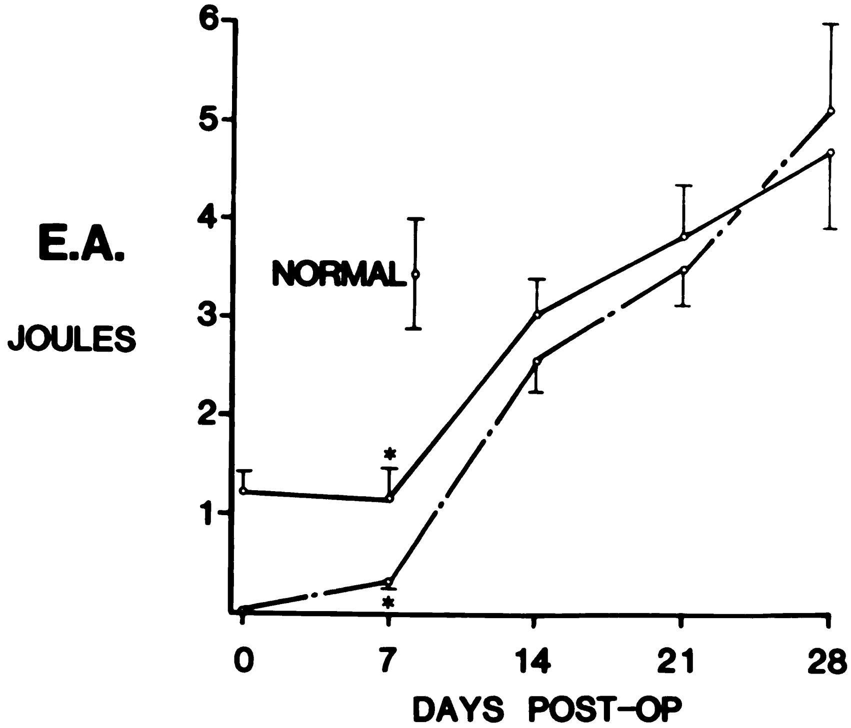

Figure 13. Energy absorbance of wounds as a function of postoperative time. The solid line (o————o) represents strength of the wound with sutures intact. The broken line (o— — —o) shows strength of wounds from which sutures were removed. Error bars are equal to one standard error of the mean, and those with asterisks have group means significantly different from the other mean at the same postoperative time.

"It has been observed that the rate at which all wounds gain strength is approximately the same during the first 14 to 21 days after wounding."(29)

However, an unusual feature of the data presented here is the rapidity with which wound strength exceeded that of normal. Nelson and Dennis found similar rates of healing in the rabbit external rectus sheath, but final wound strength even at 42 days did not reach that of the normal rectus sheath in the same animal.(35) Wound strength from the ponies in this project is shown as a percentage of normal linea alba in Table 10. There is a major difference in these figures when compared to those of rabbits, in that strength of the normal unwounded structure is exceeded by that of the wound in as little as 28 days. It is difficult to know if this interspecies difference is real, or if it results from attempts to compare dissimilar information. Differences of experimental design, testing procedures (burst strength versus breaking strength) and statistical analysis prevent valid interspecies comparison. For the larger species used in this project there is an increased total amount of suture material to act as a foreign substance, inciting increased fibrosis within the local wound environment. It is apparent that the overall picture of early wound strength (less than 30 days) is similar for ponies as has been described in rats and rabbits.(33)

At the time of necropsy, and when tissue sections were dissected for testing, there was seen to be considerable fibrosis and gross thickening of the external rectus sheath

Table 10. Wound strength as a percentage of normal.

Group No.	Postoperative Time	Sutures Intact	UL%	EA%
1	Controls	n/a	100	100
2	Postoperative	yes	38	38
		no	0	0
3	7 days	yes	32	35
		no	13	9
4	14 days	yes	100	87
		no	85	78
5	21 days	yes	119	113
		no	113	101
6	28 days	yes	129	136
		no	133	148

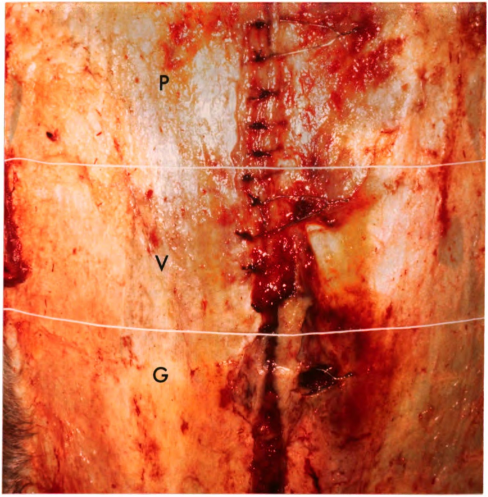

Figure 14. Postmorten incision regions. The skin has been removed from the ventral abdomen of pony number 59, 14 days after surgery, following euthanasia. At surgery the linea alba was divided into three regions in proportion to the individual pony size, as shown in the figure. The cranial region (P) was closed with polydioxanone, the middle region (V) with polyglactin, and the caudal region with (G) with chromic gut.

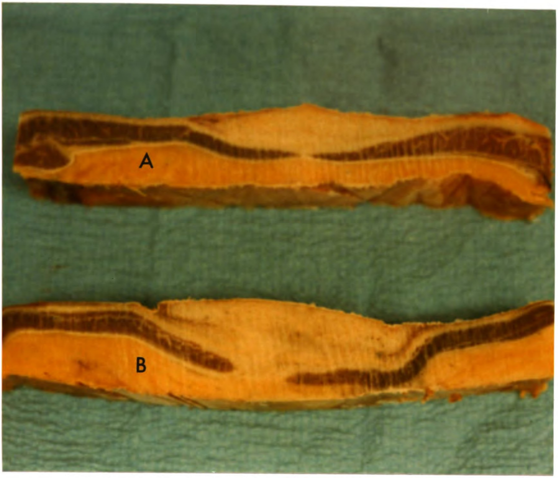

Figure 15. Transverse frozen wound section. Section (A) was from the cranial incision of pony number 59, containing PDS. Note the thicker scar in the caudal region, (B), where chromic gut was used to close the wound.

surrounding the incision line. This may be seen in the photographs in Figures 14 and 15. Especially in the region containing chromic gut sutures, it was sometimes difficult to clamp the full thickness of the scar surrounding the incision into the tissue-holding grips. This resulted in slipping of some of the specimens before complete failure had occurred (since only a small part of the total collagen mass was in contact with the grip surfaces). While the data shows at least a high minimum strength, it does not reflect what might be an actually greater strength than recorded. It is at this last healing interval that the standard error of the mean is the largest for nearly all experimental groups.

Incision region effects are described by the graph in Figure 16. Wound strength immediately following surgery and at the 28th postoperative day healing endpoint is nearly identical for the caudal, middle, and cranial regions. However, the caudal region is stronger than the cranial in the acute phase of wound healing from days 7 through 21, although this difference is significant only on the 14th postoperative day. This finding is similar to that described by Nilsson when he evaluated the strength of the rabbit linea alba in a craniocaudal axis.(45) Why animals require a stronger caudal abdominal wall than cranial or heal the caudal abdomen more quickly, at least with regard to wound strength, is not known.

In this project the degree of gross fibrosis covering

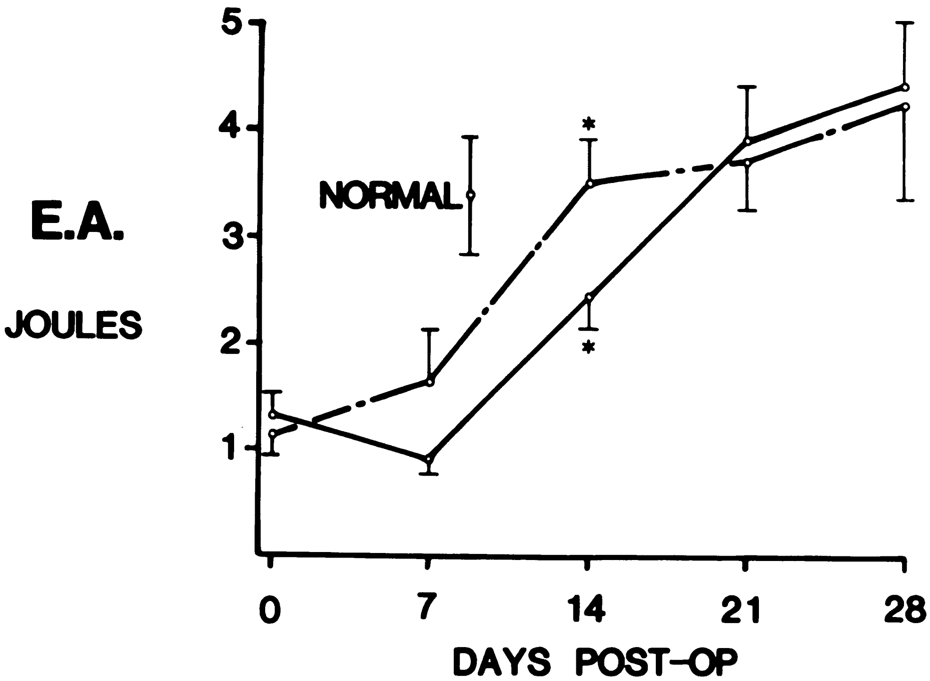

Figure 16. Energy absorbance of regional wounds. The solid line (o———o) represents the cranial segment of the linea alba; the broken line (o— — —o) shows strength of the caudal region. The middle region of the incision is not shown. The error bars are equal to one standard error of the mean, and those with asterisks have group means significantly different from the other mean at the same postoperative time. The normal datum represents the mean strength of the linea alba without regard to location.

the external rectus sheath was found to be associated with the location of the gut suture, not with the region of the abdomen. If the mass of the collagen found in healing wounds does not account for the greater strength of the caudal region, then the explanation may lie in local differences of fiber orientation and cross-linking. This finding may serve to explain the clinical observation that incisional hernias tend to occur more often in cranial incisions in humans or at the cranial limit of an incision in horses.(2)[w] Comparing the normal anatomy of the two regions, there is an increased proportion of muscle inserting closely to the LA in the cranial region. The caudal region is a broader collection of the fibrous aponeuroses of the abdominal muscle layers, which meet in a flattened curve on the midline. The sharper angle formed at the midline by the left and right sides of the abdominal wall in the cranial region may also experience increased cyclic loading by the lateral expansion of the thorax with normal inspiratory effort. Proximity to the internal attachments of the diaphragm may also produce excessive motion or forces of distraction on wounds in the cranial abdominal wall.

Suture material effects (Figure 17) were only compared in

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[w] In a review of five cases of incisional hernia following celiotomy at the University of Missouri Equine Center, all were located at the cranial limit of the abdominal wall incision.

groups 3, 4, 5, and 6, as group one had no sutures, and in group two there was no breaking of sutures in those section tested. Wounds sutured with gut were found to be significantly stronger only in terms of EA than those closed with PDS on the 28th postoperative day. This information suggests that the increased fibrosis elicited by chromic gut is capable of absorbing more total energy on the way to failure, but does not confer any advantage as far as increasing the breaking strength. This finding is in agreement with Peacock's observation that ". . . we actually measure the strength of the strongest component."(29) Donaldson in a prospective trial comparing PGA, chromic gut, and polypropylene in 231 human laparotomy patients found no significant difference in the rates of wound dehiscence or incisional hernia.(86)

Interpretation of the results of this thesis requires awareness of their source: The *in vitro* testing procedures used here cannot be considered to mimic the loads and cycling of the connective tissue scar *in vivo*. Virtually all wound strength research is designed on the basis of a single observation (for each tissue sample) which follows application of a sudden overwhelming stress. The normal physiologic stresses encountered by the wound may be very different. In the case of the healing linea alba, the constant motion required by inhalation, the frequent occasions to use the abdominal press, changes of posture, and even whole body activity probably all combine to

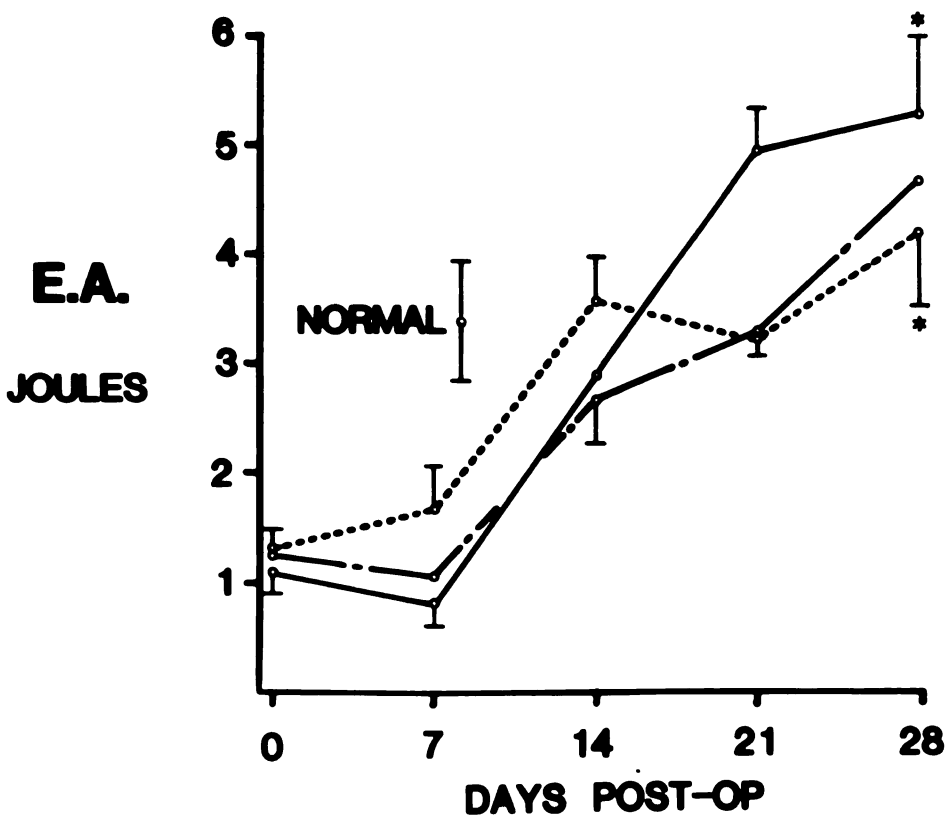

Figure 17. Energy absorbance of wounds by suture material type. The solid (o————o) represents wound strength of the linea alba closed with chromic gut, the broken line (o— — —o) wounds closed with polyglactin, and the dashed line (o– – – –o) wounds closed with polydioxanone. The error bars are equal to one standard error of the mean, and those with asterisks have group means significantly different from the other means at the same postoperative time.

produce gradual elongation of the scar. It seems reasonable to suppose that the early scar, composed of Type III collagen in a low-strength, disorganized mass is most susceptible to gradual elongation in response to these momentary high-stress forces. Later, when replacement by Type I collagen fibers aligned in the direction of local physiologic stress forces has occurred, elongation of the scar may be arrested. While there have been several risk factors identified from which later development of an incisional hernia may follow, the pathophysiology is not at all clear.

A common problem in tensometry of the linea alba is the finding that this structure (or its mature wound after sufficient healing has occurred) is stronger than the entire thickness of the abdominal wall only a few centimeters away. The conclusion is often drawn that the wound or linea alba is stronger than the lateral abdominal fascia. The problem remains: 1) Wound strength is still unknown, and 2) The conclusion of strength is based on sudden failure of the testing method. The appearance of incisional hernias (especially late hernias) is a clue that cyclic loading over time is, to the wound, a force more difficult to resist. Perhaps the healing linea alba is stronger than the more lateral abdominal wall after 21 days because it needs to be. We have come full circle to the problems of adequate tissue gripping for this anatomic structure and the need for more physiologic (cyclic) wound testing.

The problem of designing a system of tissue grips that can firmly hold the complex cross-section of muscle and fascia which is the abdominal wall will probably be solved. A clamp for large tendons has been described which circulates a refrigerant through its hollow structure, freezing the tendon between its jaws.(87) This clamp has exerted in excess of 13,000 Newtons without slippage of the tendon. Mechanical testing equipment is available which may be programmed to load a tissue sample in a controlled cycle. It would still be desirable to maintain the section "alive" throughout the process of controlled mechanical fatigue, a far more difficult problem to solve.

Implications for the Surgeon

The surgeon should interpret with caution the findings described in this thesis. For example, it would be premature to believe that abdominal wounds have regained normal strength by the 14th postoperative day, and allow strenuous activity by a patient at that time. In fact, it may be true that celiotomy wounds withstand severe, isolated stress (distraction forces) after the second week following surgery quite well. The question of how well such early wounds withstand repeated distraction forces remains unanswered. Similarly, many accepted guidelines of suture selection argue against the use of chromic gut suture. Synthetic absorbable sutures now available are far stronger, retain their strength longer, are less prone to inciting wound sepsis or sterile abscesses, and tend to evoke less severe inflammation of the wound. It was previously thought possible that polydioxanone would contribute sufficiently to wound strength beyond the 14th postoperative day (and beyond the time afforded by other absorbable suture materials) that it would provide a long term advantage. Instead, the conclusion which must be drawn is that sutures do not contribute to wound strength in the pony's abdominal wall beyond the 13th postoperative day. The persistence of foreign material (suture) across the healing wound may act as a stress-riser, and actually weaken the collagenous scar.

The needs of the surgical task at hand will continue to dictate the appropriate site for incision. If the cranial celiotomy wound is more at risk for later herniation, as suggested by the results of this project and clinical observations, then perhaps those cases which require cranial incision should be managed more conservatively in the postoperative period. At least the data obtained here would suggest that there may be greater risk of wound dehiscence of cranial incisions than those placed in the caudal region, up through the 20th postoperative day.

The results and conclusions described here are taken from an experimental model (ponies). Pending further clinical or laboratory studies which examine the dynamics of wound strength of the linea alba in full-sized horses, it seems reasonable to apply the findings described above to surgical practice involving all equids.

CONCLUSIONS AND SUMMARY

"Surgeons are pragmatic creatures, more interested in departures that offer real benefits to patients than in those which satisfy statisticians."

Evans and Pollack, 1984

In this project wound healing in ponies has been examined and has been defined from the particular need for strength and functional closure of the abdominal wall. This is not the only valid criteria of healing, but may be considered the most important for this particular anatomic structure. A narrow definition of wound strength was applied to the dynamics of tissue healing in the abdominal wall of ponies. The influences of anatomic site and different suture materials were also investigated.

It was determined that there is a rapid gain of strength in the healing linea alba between the 7th and 28th days, preceded by a slight decrease in strength in the first postoperative week. This pattern of increasing wound strength is substantially the same as has been described in other species. The rate of wound strength increase in ponies may be faster than that seen in rabbits, based on per cent of strength of the normal linea alba. The finding that most wounds analyzed in this study had a final strength greater than that of the linea alba in the normal control ponies is not difficult to account for. On gross inspection of the thickness of the fibrous scar at the time of sample dissection, the greater thickness of the healed incisions compared to the normal rectus sheath and linea alba was obvious. Allen obtained similar results in horses with different suture patterns and testing methods than were used here, finding that even as early as the 12th postoperative day the wound strength may equal or exceed that of the normal structure.(27) Quantitative measurement of scar mass was not a design feature of this project, but should certainly be considered in future research in this area. Energy absorbance, or failure energy, is the more sensitive indicator of wound strength and was able to discern significant differences in the data not detectable by ultimate load (breaking strength).

The wound in the caudal abdomen regained strength more quickly than did the cranial wound, although by the 28th postoperative day they were similar. The physiologic mechanism which is responsible for this is not known, although it has been described in other species. This may be an artifact resulting from the particular methods employed to grip and distract collagenous tissue. It seems unlikely that the process of wound healing is capable of such "fine-tuning" within a given anatomic structure. The finding of decreasing strength in the cranial limit of ventral abdominal incisions is perhaps supported by clinical events: That incisional hernias in horses are usually in the cranial part of the wound made earlier.

Lastly, the use of chromic gut suture in ponies is attended by extensive fibrosis of the superficial surface of the external rectus sheath. The total mass of scar tissue covering the incision site may explain the fact that at the end of the 4th postoperative week, these wounds were significantly stronger than those containing PDS, the least tissue-reactive suture material. Of greater concern to the surgeon is the fact that on the 7th postoperative day, those regions closed with chromic gut had lost an appreciable part of their strength.

APPENDICES

APPENDIX A

TABLE 11. Sizes of suture materials

Metric	USP Sizes Textiles	USP Sizes Gut	B & S Wire Gauge
0.1			
0.2	10-0		
0.3	9-0		
0.4	8-0		
05	7-0	8-0	41
0.7	6-0	7-0	38-40
1.0	5-0	6-0	35
1.5	4-0	5-0	32-34
2.0	3-0	4-0	30
3.0	2-0	3-0	28
3.5	0	2-0	26
4.0	1	0	25
5.0	2	1	24
6.0	3 & 4	2	22
7.0	5	3	20
8.0	6	4	19
9.0	7		18

APPENDIX B

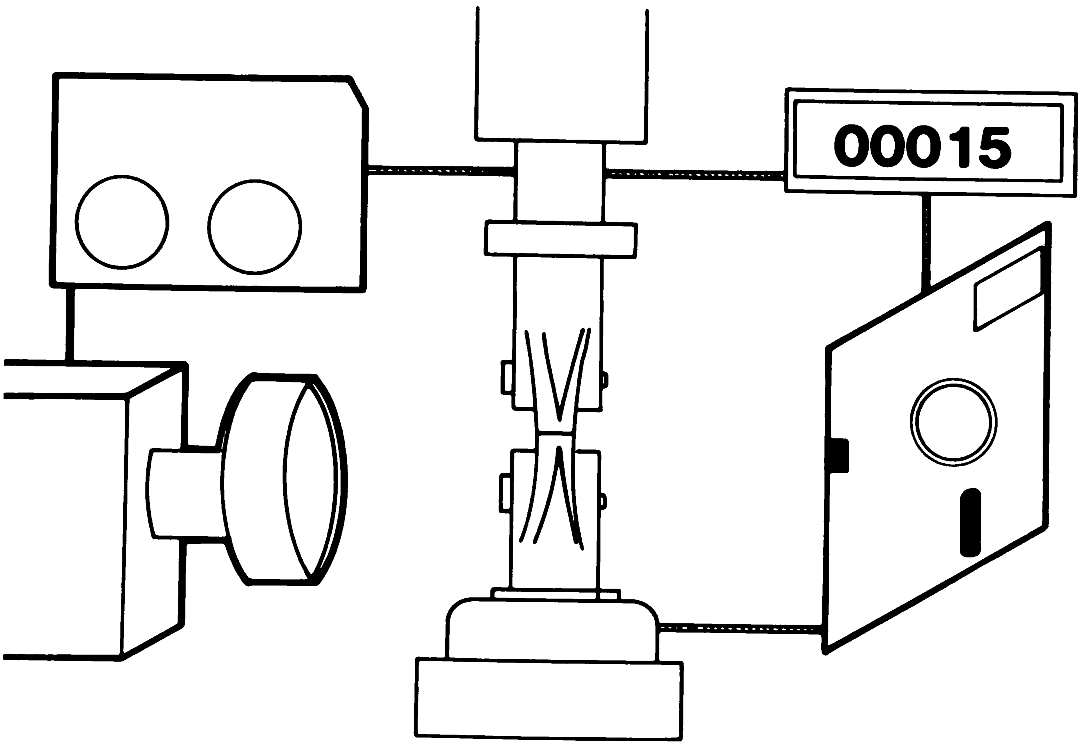

Figure 18. Schematic of sample testing.
Data from each wound sample was recorded on magnetic disks, including load, time signal, and position of the distracting hydraulic piston. The visual appearance of wound failure was recorded by videocamera on tape with the same time signal mark.

APPENDIX B

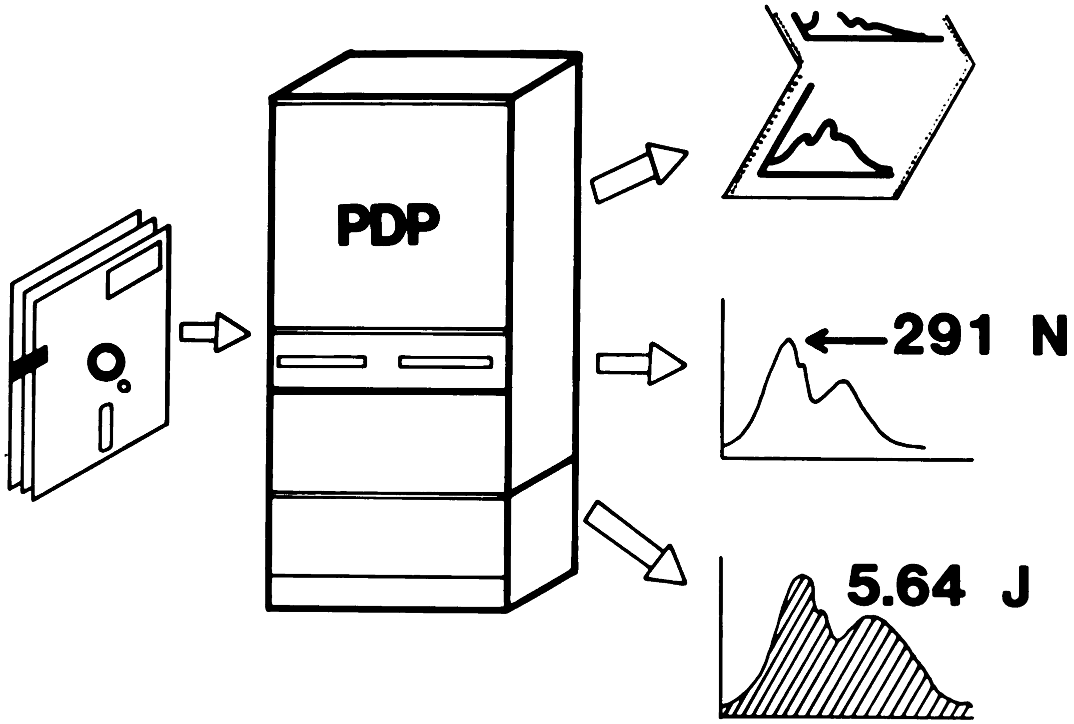

Figure 18, continued. Schematic of sample testing. The data from all wound segments tested was processed to produce plots of load versus distance, ultimate load (breaking strength), and energy absorbance (failure energy).

APPENDIX C

TABLE 12. Filtered data, with calculated units. GROUP 1

Pony: DANNY	Ultimate Load, N	Energy Absorbed, J
Section Suture		
1	194	3.7
2	243	3.1
3	291	2.9
4	408	3.2
	439	4.2
6	377	3.5
Pony: HOLLY		
Section		
1	120	1.0
2	102	1.2
3	145	1.2
4	260	2.1
5	283	1.9
6	133	2.4
Pony: MARIA		
Section		
1	200	3.5
2	241	3.1
3	237	2.5
4	219	3.1
5	180	2.3
6	297	3.1
Pony: MUDD		
Section		
1	175	3.9
2	291	4.2
3	390	7.4
4	427	8.4
5	263	3.7
6	259	6.1
Pony: TOBY		
Section		
1	175	4.0
2	326	2.5
3	394	5.9
4	246	3.2
5	192	2.8
6	168	2.9
Pony: WILMA		
Section		
1	321	3.3
2	391	3.4
3	247	3.7
4	243	3.3
5	308	2.9
6	202	3.4

TABLE 12, continued. GROUP 2

Pony: A-H Section	Suture	Ultimate Load, N	Energy Absorbed, J
1	V	165	1.5
2			
3	G	102	2.0
4			
5	P	79	1.4
6			
Pony: BARNEY			
Section			
1	V	65	0.4
2			
3	G	52	0.6
4			
5	P	46	0.3
6			
Pony: GINGER			
Section			
1	G	133	1.2
2			
3	P	126	1.7
4			
5	V	113	1.3
6			
Pony: PEGGY			
Section			
1	P	192	1.7
2			
3	V	113	1.4
4			
5	G	99	1.6
6			
Pony: SARAH			
Section			
1	V	110	1.3
2			
3	G	81	0.9
4			
5	P	83	1.9
6			
Pony: WALDO			
Section			
1	P	56	0.8
2			
3	V	83	1.2
4			
5	G	82	1.3
6			

TABLE 12, continued GROUP 3

Pony: ARLO Section	Suture	Ultimate Load, N	Energy Absorbed, J
1	G	110	1.7
2	G	46	0.5
3	P	108	1.2
4	P	48	0.5
5	V	722	0.8
6	V	580	0.4
Pony: DAPHNE			
Section			
1	P	52	0.4
2	P	18	0.1
3	V	102	1.2
4	V	41	0.3
5	G	48	0.8
6	G	28	0.3
Pony: GODMOTHER			
Section			
1	V	170	2.2
2	V	39	0.5
3	G	29	0.3
4	G	37	0.3
5	P	114	1.3
6	P	66	0.4
Pony: GRANDPAW			
Section			
1	P	103	1.7
2	P	40	0.3
3	V	70	0.8
4	V	32	0.6
5	G	14	0.3
6	G	30	0.2
Pony: OTTO			
Section			
1	G	37	0.3
2	G	41	0.3
3	P	125	2.0
4	P	37	0.2
5	V	72	1.2
6	V	31	0.4
Pony: WENDY-O			
Section			
1	V	153	3.5
2	V	16	0.1
3	G	71	0.4
4	G	14	0.1
5	P	47	1.1
6	P	13	0.1

TABLE 12, continued GROUP 4

Pony: ADOLPH Section	Suture	Ultimate Load, N	Energy Absorbed, J
1	P	325	3.2
2	P	389	3.2
3	V	248	2.8
4	V	177	2.8
5	G	226	3.8
6	G	180	1.6
Pony: BLONDIE Section			
1	V	406	4.7
2	V	286	2.8
3	G	256	3.6
4	G	256	4.6
5	P	213	2.4
6	P	186	1.7
Pony: FLOYD Section			
1	V	354	3.9
2	V	212	2.4
3	G	374	3.0
4	G	148	2.4
5	P	157	2.0
6	P	183	1.6
Pony: NORMA Section			
1	G	293	4.6
2	G	224	3.3
3	P	326	3.5
4	P	280	3.3
5	V	187	2.1
6	V	203	3.4
Pony: SNUFFY Section			
1	G	275	2.3
2	G	269	2.3
3	P	231	4.0
4	P	178	2.5
5	V	272	2.8
6	V	267	2.4
Pony: ZELDA Section			
1	P	307	2.6
2	P	319	4.3
3	V	117	1.8
4	V	142	1.8
5	G	187	1.6
6	G	150	1.3

TABLE 12, continued GROUP 5

Pony: DELBAR Section	Suture	Ultimate Load, N	Energy Absorbed, J
1	P	405	5.5
2	P	365	2.9
3	V	246	2.5
4	V	356	5.4
5	G	326	3.6
6	G	271	4.3
Pony: KATIE			
Section			
1	G	239	4.1
2	G	234	2.7
3	P	314	2.6
4	P	240	2.8
5	V	336	5.2
6	V	212	2.8
Pony: MARVIN			
Section			
1	P	254	3.2
2	P	435	3.5
3	V	495	5.1
4	V	410	3.9
5	G	392	3.9
6	G	291	4.8
Pony: MINERVA			
Section			
1	G	258	3.5
2	G	339	4.1
3	P	310	2.9
4	P	192	3.6
5	V	413	5.5
6	V	265	3.7
Pony: NORMAN			
Section			
1	V	222	3.1
2	V	269	1.7
3	G	345	5.8
4	G	464	4.5
5	P	249	2.5
6	P	223	2.4
Pony: PEDRO			
Section			
1	V	294	3.2
2	V	127	2.1
3	G	309	4.4
4	G	381	4.4
5	P	257	2.8
6	P	293	3.1

TABLE 12, continued GROUP 6

Pony: BEAU Section	Suture	Ultimate Load, N	Energy Absorbed, J
1	V	444	5.6
2	V	461	5.6
3	G	377	5.6
4	G	341	8.4
5	P	392	4.7
6	P	330	6.6
Pony: BONNIE			
Section			
1	V	145	2.1
2	V	396	3.9
3	G	399	6.0
4	G	263	4.2
5	P	250	4.0
6	P	288	6.6
Pony: GUS			
Section			
1	G	155	1.9
2	G	322	3.8
3	P	211	2.5
4	P	122	0.9
5	V	243	1.9
6	V	203	3.6
Pony: MICKEY			
Section			
1	P	369	6.0
2	P	635	11.2
3	V	439	6.0
4	V	461	5.9
5	G	374	6.4
6	G	386	5.4
Pony: REUBEN			
Section			
1	G	277	2.8
2	G	447	3.9
3	P	282	4.1
4	P	318	3.0
5	V	218	5.0
6	V	208	5.0
Pony: VERN			
Section			
1	P	669	7.0
2	P	519	7.0
3	V	462	8.6
4	V	338	3.5
5	G	431	4.4
6	G	283	3.8

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