MECHANICAL AND BIOLOGICAL STUDY OF REPAIR OF FLEXOR TENDON

by

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ABSTRACT

The results of primary flexor tendon surgery are often poor and surgery of this type is difficult. Many factors have been researched by surgeons, but very little work has been done from a mechanical viewpoint. The work in this project examined :

1) The features of suturing techniques which influence their holding power and uses the knowledge gained to design an improve suture technique.
2) Normal vascular anatomy of chicken's flexor tendon in the third toe.
3) The effects of various factors on tendon softening and adhesions after trauma.
4) Two new suture materials in tendon repair from mechanical and histological aspects.

Fresh human cadaveric tendon repairs were tensile tested and simultaneously x-rayed. Desirable features were: placing the peripheral suture in the tendon fibres instead of the epitenon layer, and elimination of locking loops and criss cross configurations. An improved suture technique was designed which is three times stronger than Kleinert's technique.

Indian ink and barium sulphate perfusions were carried out before any other studies were done on chicken's flexor tendon. The vascular anatomy of the third toe of the chicken was found to conform to the general pattern observed in man.

Experiments on the chickens digital flexor tendon were carried out to examine factors influencing softening and adhesions. This study showed that

softening was associated with inflammatory changes within the tendon as part of the healing process and it is more extensive at the avascular zone of the tendon. This study also suggested that the interruption of vincular blood supply to the tendon is associated with increased adhesion formation and decreased tendon gliding.

Normal human tendon suturing technique was then applied to surgically severed digital flexor tendons in the feet of chickens, using absorbable polytrimethylene carbonate (Maxon) and Non absorbable Polybutester (Novafil) in the vascularized zone. Mechanical testing showed that both sutures can keep their strength long enough to allow union. However, high tissue reactivity of Maxon during its dissolution is a main disadvantage. Because of good strength, ease of handling, and slight or minimal tissue reaction, a possible advantage may exist for the use of Novafil sutures in hand surgery.

The knowledge derived from mechanical/ biological work in this thesis will help to improve the results of surgery to the finger flexor tendons.

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Chapter 1: Introduction to primary flexor tendon repair within the fibro osseous tunnel

1.0 Introduction

The specific problems with primary flexor tendon repair in the hands are: Tendon suture breakdown, rupture of the repair, adhesion between repair and surrounding tissue, weakening of the tendon stumps, and tendon healing and nutrition.

The actual process of the repair of the divided tendons, the source of the tissue that makes the union between the tendon stumps, has been and still is, the subject of considerable controversy. The poor vascular supply of tendon and the necessity of good vascular supply to reparative tissue are two factors that appear to be constantly working against the surgeon. The force of this fact is more strongly brought out when it is remembered that adequate revascularization of tissue requires immobilisation, while immobilisation of injured tendon favours the formation of adhesions which will limit the function. The necessity of function during healing would seem to be incompatible with the immobilisation necessary to obtain efficient vascularization. The technique by which tendon should be sutured is a perplexing problem. Despite much work by surgeons to try to improve their techniques, the results of surgery are still poor. The main factors which cause the poor results are that either the repairs pull apart or they are fixed by adhesions. It is thought that a major contributory factor is the inability of surgeons to design a practical suturing technique with sufficient strength. It has been shown that the tendon can withstand loads in excess of 1000 N, yet the

surgical repairs fail below 50 N. It is not surprising that tendon repairs can fail by being pulled apart accidentally after surgery. An alternative scenario is that the therapist is so cautious about moving the repaired tendon that the finger becomesfixed by scar tissues, so again the finger will not function. The possible significance of softening of the tendon stumps from approximately the third to the twelfth day has also led to a continuing controversy among surgeons.

A large amount of biological research has been directed towards the above problems, with little or no mechanical considerations. This chapter will review the most significant contributions to flexor tendon surgery and discuss today's popular methods.

1.1. Repair methods used in primary flexor tendon repair

The ancient and medieval surgeons were handicapped not only by the lack of knowledge of wound infection, but also by the fact that it was not until the middle of the eighteenth century that a clear distinction was accepted between the tendons and nerves, despite the fact that Galen had described the differential anatomy of tendons, nerves, and ligaments in the second century. Without doubt, the catastrophic possibilities of this lack of knowledge were enough to discredit most of the early operative repairs of tendon wounds.

Galen also warned against poor results of tendon suture. This warning came from the fact that he considered the tendon a mixture of nerve and ligaments, and he considered that suture within nerve substance was likely to be followed by severe pain, twitching and convulsions.

Aveciena (cited by Kaplan, 1966), in the tenth century, strongly advocated tendon suture. It was somewhat over two hundred years later that Italian surgeons asserted that nature was unable to unite divided tendons, and that the surgeon could bring the stumps together better than nature. About the same time (early in fourteenth century) the French surgeons, evidently under the influence of Italian surgeons, attempted with but a modicum of success to defend the closure of tendon wounds.

Another two centuries elapsed before one reads in the work of Pare (cited by Adamson and Wilson, 1961) in the sixteenth century of successful instances of tendon suture, and it is logical to assume that he himself had practised it. Still there was no general acceptance of surgical procedures on tendons. Galen had said fourteen hundred years before that a prick of a nerve or tendon would

lead to convulsions, and, without attempting experimental confirmation of this opinion, the surgical profession accepted this dictum as a fact.

During the seventeenth century a few investigators reported successful tendon sutures on dogs. Lanzweerde (cited by Kaplan,1966), in seventeenth century, divided the achillies tendon in dogs and sutured it. Healing occurred and full functional use of the leg returned.

Meekern (1682) tested crudely the sensitivity of tendon tissue to injury. He found no evidence that the tendons were sensitive or that injuring them caused pain. In the domain of clinical surgical intervention, however, tenorraphy was still in disrepute. The maxim never to pass a needle through a tendon had such a great hold on the profession that Bienaise in dealing with a wound in the palm, instead of suturing, wrapped the suture around each end of the divided tendon and then tied the suture together. A good result was achieved in this case (cited by Bunnell, 1928). Haller, in the middle of the eighteenth century, demonstrated that tendons were insensible and this meant that operative procedures on them were to become generally accepted.

Although the fundamentals and principles of tendon surgery were understood, it was towards the later part of the nineteenth century and in the first half of the twentieth century that real progress was shown. Primary tendon suture, transplantations of tendon and muscle, and tendon grafting became well established. However, the early tendon surgeons who used primary repair suffered poor results, and functional failures were numerous; especially as far as the flexor tendon in the sheath was concerned. So much so that Bunnell (1918) called it "no man's land". Following the pioneering work of Verdan(1960, 1979) and Kleinert and associates (1974, 1980, 1981) primary

flexor tendon repair within the digital sheath has become a routine under favourable circumstances. Results that originally were thought to be no better than those obtained with flexor tendon grafting and transplantation have been shown to be superior in almost all studies.
The failures of early tendon surgeons were apparently due to insufficient knowledge of the physiology of tendon structures and movement, the trend of wide dissection, continuous immobilisation for one month and a strangulating suture technique.

Bunnell (1918) reviewed the anatomy and physiology of the hand and described the principles of tendon surgery in the hand with preservation of the pulleys, careful post operative management, and placing the incision away from the mid line of the fingers. Although the results were significantly better, the main problem was still unresolved- the prevention of adhesions and preservation of gliding mechanism and the blood supply.

Based on a study by Mason and Allen (1941), it was generally accepted that a period of 2-3 weeks of immobilisation was beneficial to promote early tendon healing. This method ensured the formation of some binding adhesions of tendon to adjacent soft tissue during the period of immobilisation, but it was hoped that these could be stretched or broken in the course of the post operative active therapy programme. The main fear with regard to early motion was tendon repair gap formation or actual rupture because the tensile strength of the repaired area was diminished during the first two weeks postoperatively (see section 1.4). Most of the techniques developed during the last few decades for flexor tendon repair were based on the assumption that immobilisation for three weeks would follow the repair. The classical techniques based on these concepts were the figure eight suture (Bunnell

1944), and Mason and Allen suture (1941) (see fig 1.1a and 1.1b). As demonstrated later by Caroll and Match (1974), if the figure eight suture was subjected to early motion, it would convert into a single loop by longitudinal separation of tendon fibres, which eventually allowsdisruption of the repair. This technique also interferes with intratendinous blood supply and can cause ischaemia, necrosis and adhesion (Berdgljung, 1970; Matthews and Richards,1977).

The results obtained by immobilisation, however, were not satisfactory. Two alternativeshave been suggested:

1) To eliminate tension on the repair site while still somehow permitting motion, Brunelli et al., (1983) described a unique suture technique that takes tension away from the tendon juncture by moving the suture fixation points well away from the area of the juncture (see fig 1.1c) . Other techniques such as a barbed wire suture (Mckenzie, 1967; Shaw, 1968) work on the same principle. Such innovations deserve additional study (see fig 1.1d).

2) To increase the strength of a repair to a point sufficient to permit early active flexion and extension. The weight of current practice seems to be in favour of this suggestion.
To achieve a better strength of a repair Kessler and Nissim (1969) designed a new technique based on the Mason and Allen tendon suture (first described by Kirchmayr in 1917). It was further reinforced by two knots that were placed symmetrically on both sides of the repaired tendon, and four " locking loops" at the corners (see fig 1.1e). As intratendinous vessels lie in the dorsal half of the flexor tendons (Caplin et al., 1975), it was customary to place the Kessler stitch in the volar surface of the tendon. Kleinert and Cohen (1974) modified

this technique slightly by placing the knot between the tendon ends (see fig 1.1f).

Verdan (1979) and Ketchum et al. (1977) modified this technique further by increasing the number of locking loops along the side of the tendon in order to increase the strength (see fig 1.1g and 1.1h). These techniques were designed to grasp the lateral strip of the tendon away from its blood supply. The Ketchum technique was further modified by Becker (1978), but he used such a fine suture that one wonders if this is the cause of early rupture he reported (see fig 1.1i).

A new "intratendinous" suture method was developed by Tsuge et al (1975). Although the circulatory disturbances were claimed to be minimal, excessive manipulation of tendon during the insertion of this suture method might cause adhesions (Bunnell 1941: Potenza 1963) (see fig 1.1j). The above techniques improved holding power compared with the traditional Bunnell technique (Urbaniak et al., 1983; Ketchum et al.,1977; Wray and Weeks, 1980; Defeino et al., 1986). Compared with the magnitude of tensile forces that might be expected to act on a tendon juncture during normal active motion, however, these advances were not sufficient to permit active motion without a significant risk of rupture. Savage (1985) derived a very strong technique (see fig 1.1k). Compared to the above techniques it has been shown to have three times the tensile strength and to allow one tenth the gap to form between the tendon ends under load. The stitches do not constrict the blood supply and it is claimed to allow early mobilisation. Savage took into account the load sharing properties of multiple strands and incorporated anchorage to the tendon substance peripherally. However, it seems to be very difficult to put in, because the locking stitches mean that the length must be adjusted at each pass

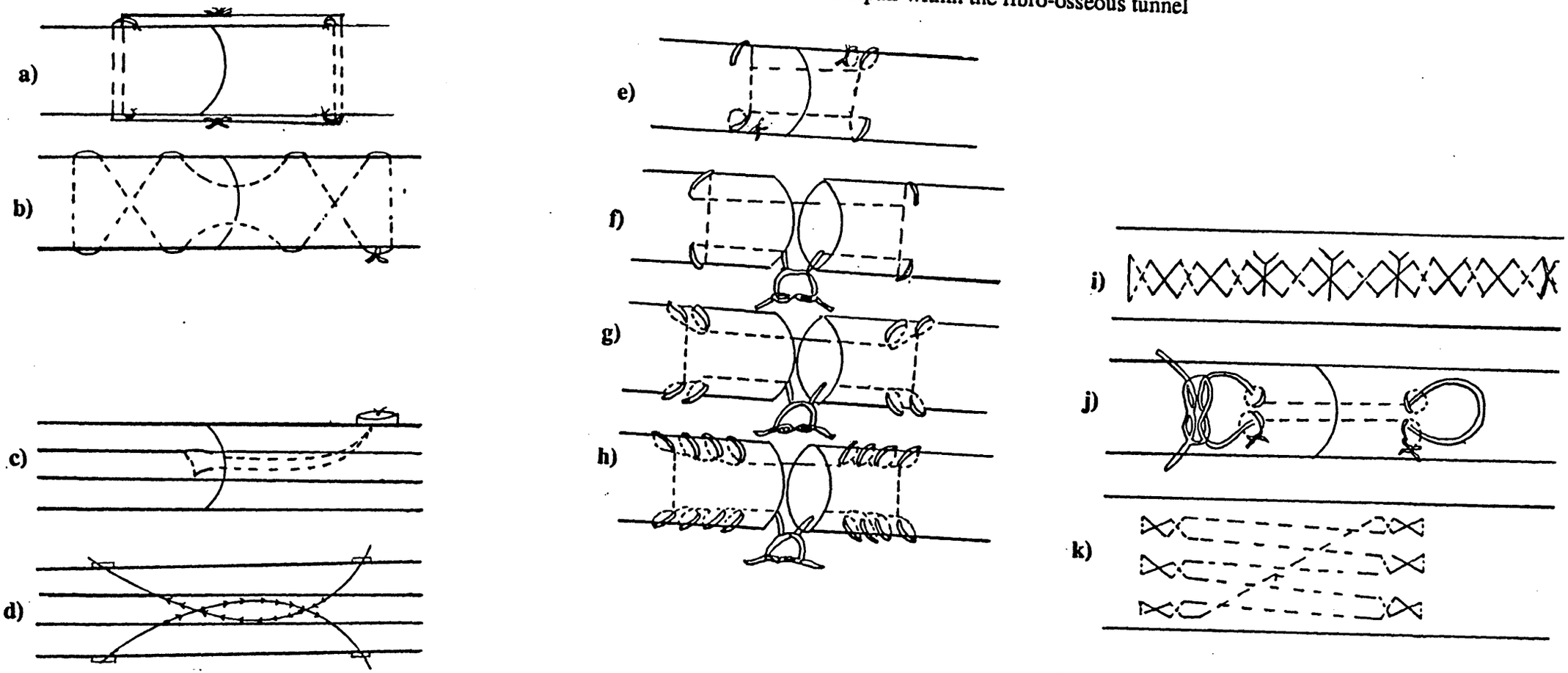


Fig 1.1: The different methods of tendon anastomoses. a) Mason and Allen, b) Bunnell, c) Brunelli, d) Shaw, e) Kessler, f) Kleinert, g) Verdan, h) Ketchum, i) Becker, j)Tsuge, k) savage

across the repair. The suture X technique by McDowell et al (1987) is similar to this technique but non continuous.

A running circumferential suture is usually used to approximate the margin of the tendon after placing the above core stitches but not with Savage. Lister (1983) emphasized that circumferential suture should be placed in the superficial (epitenon) layer and not within the tendon fibres, since that would result in eversion of tendon bundles and probably adhesions later on. This recommendation was in line with the view that peripheral stitches were only to tidy up the repair and not to contribute to strength. However, it has been shown that peripheral stitches do contribute to strength (Wade et al., 1986) and delay the onset of gap formation (i.e functional failure point) under load. The peripheral stitches commonly in use at present are as follows: interrupted, interrupted Lembert, interrupted vertical mattress, over and over, interrupted horizontal mattress, interrupted Halsted, and continuous Halsted (Nealon, 1979) technique (see fig 1.2). The strength of these stitches has not yet been determined.

Studies of suture techniques undertaken until now have sought only to compare the holding power of stitches rather than trying to identify the fundamental reason why particular suture techniques are good or not. This progress has been made by trial and error, rather than by design.

One aim of this thesis is to investigate the features of suturing techniques which influence their holding power. This could relate to the suture itself, such as diameter or roughness, or to layout of the stitches, such as locking loops, criss cross, or to placing the suture in different layers such as epitenon or

within the tendon fibres, and use the knowledge thus gained in designing an improved suture method.

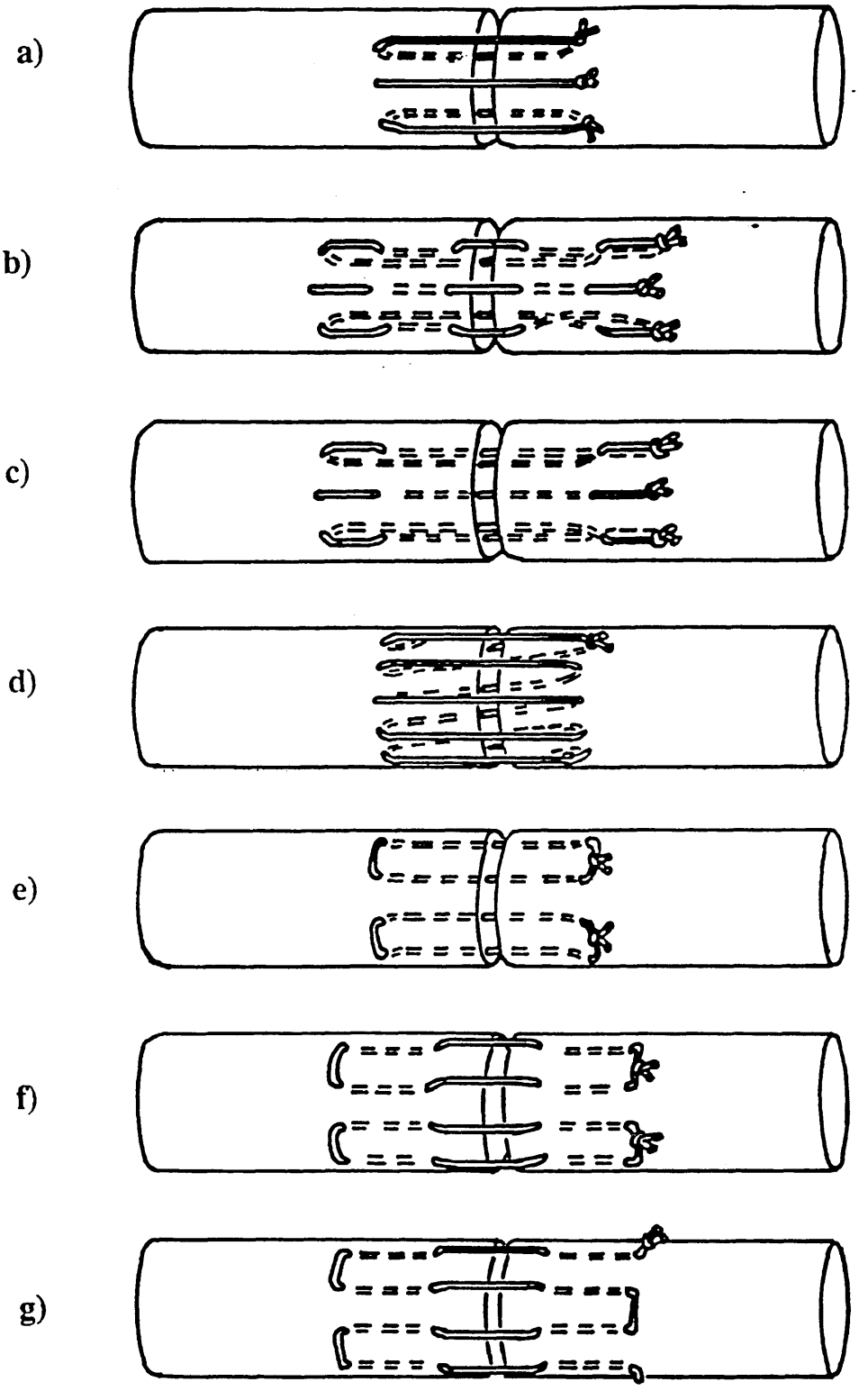


Fig 1.2: peripheral stitches commonly in use at present. (a) interrupted , (b) interrupted Lembert, (c) interrupted vertical mattress, (d) over and over, (e) interrupted horizontal mattress, (f) interrupted Halsted,(g) continuous Halsted

1.2 Absorbable and non absorbable suture material used for primary repair of flexor tendon

The use of the thread and needle for tendon repair is described in the literature as far back as the fourteenth century. Since then a great many materials have been used for these purposes: dried gut, dried tendon, ligaments, strip of hide, horse hair, women's hair, leather, bark fibres and textile fibres of various kinds. Before the introduction of antisepsis, the use of suture presented great problems, since their application necessarily implied infection. Pus formation and secondary haemorrhage were common complications. The introduction of "antiseptic" by Lister (1869) meant a considerable improvement with regard to infection rate. When sterilisation of suture materials with potassium iodide was introduced, the rate of infection was further reduced. As time went by other methods of sterilisation were discovered and nowadays suture materials are sterilised with ionizing radiation or with ethylene oxide.

There are two basic properties of suture materials in tissue that are important to the surgeon employing them for tendon repair. These are inertness of the suture in tissue and the ability of the suture to maintain its strength during tendon healing. Until 1930, the suture materials used for tendon suturing were cat gut, silk, and to a lesser degree, linen and cotton. Silk was the most popular one with regard to ease of handling. In 1940, silk began to give way to stainless steel, because of its high tensile strength and non reactivity. Stainless steel was opposite to silk, it was the least reactive suture and the hardest to handle.

Polyamide (Nylon) was the first synthetic suture used in tendon suturing.

Mersilized polyester (Dacron), and polypropylene (Prolene) are suture materials that have competed with polyamide (Nylon). All are relatively non reactive, and have a greater ease of handling than monofilament nylon, which is very springy and requires four knots to prevent untying. A close relative to Nylon is Supramid. Monofilament Nylon is springy and the tensile strength is reduced by any nick in the suture, which reduces its diameter at the site of that weakest link. It is also made into a braided suture which has a greater ease of handling, but the interstices of the braiding are an inviting host to both fibroblasts and bacteria. Supramid, on the other hand, is made into polyfilament strands ensheathed by a tube of caprolactan, which gives it the appearance of being a monofilament suture. The internal polyfilament structure, however, endows the suture with a much improved ease of handling and knotting.

For many years the only absorbable suture material was catgut, either plain or chromicized. The inflammatory reaction it induces is intense but short lived (Madsen, 1953; Postlethwait, 1959(b)). Plain catgut loses about 60% of its strength after seven days, therefore, it is not an appropriate suture for tendons. However, in the last decade advances in polymer chemistry have been applied to absorbable suture technology. The three major types available today are as follows: polyglycolic acid (PGA, Dexon), polyglactin 910 (Vicryl), and polydioxanone (PDS). These sutures degrade by hydrolysis and are absorbed by the body with the minimal tissue reaction. Their biological behaviour in terms of breaking strength retention, tissue reaction, and absorption are more uniform and predictable than catgut(manufacturer's data). Thus there is less of an inflammatory reaction around the tendon juncture.

Because of the inherent rigidity of the polymers, monofilament sutures produced

from polyglyactin 910 and Polyglycolic acid are too stiff for general surgical use. These polymers can be used as a monofilament suture only in the very finest sizes. However, polydioxanone is a novel polymer which can be converted into a uniquely flexible monofilament suture of all sizes and lose 50% of their strength at four weeks (manufacturer's data). However, four weeks is a short time for safety in tendon repair.

Ketchum et al (1977) compared 20 tendons repaired with polyglycolic acid suture to 20 repaired with a polyester sutures. At one month there was of 50% diminution in the tensile strength of the polyglycolic acid group compared with the group repaired with polyester fibre.

Bruck and Schlogel (1986), in a clinical study, performed 67 tendon sutures on 29 patients using polydiaxonone. He reported excellent results.

Ketchum et al (1977) investigated the resistance to gap and rupture producing forces afforded by monofilament stainless steel, multifilament stainless steel, Supramid, monofilament polyamide, monofilament polypropylene and braided polyester fibre. Supramid emerged as the strongest of the synthetic suture repair at three weeks. Monofilament stainless steel produced the greatest resistance to both gapping and eventual rupture and was shown to have twice the strength of the multifilament stainless steel and 1.7 times the strength of the strongest synthetic suture, braided polyester fibre. This strength decreased by 50% after three weeks. Steel, however, was felt to be too inelastic and brittle to serve as an effective repair material for severed flexor tendons.

Mangus et al (1971) also showed that monofilament stainless steel, although

having the advantage of less tissue reaction than most materials, is too stiff to serve well and long as a buried suture. In their experience using wire in tendon, even with a careful technique there was a real tendency for the wire to saw through the tendon. They believed that this was because wire had a tensile strength far greater than the tissue it was approximating. Also they believe that the inherent kinking tendency of wire is a drawback. They studied polyamide and stainless steel in several variables and found that stainless steel required five times as much driving force as did nylon for pull out suture, but with regard to breaking strength stainless steel was stronger (1.4 to 1). However, they could demonstrate microscopically the effect that manipulation produced on stainless steel wire. They were surprised to find that even a gentle rubbing of stainless steel with the smooth side of a needle holder may produce marked flaking, with a very jagged tooth like excrescence of the metal.

Surgi (1971) studied the reactions of flexor tendons in dogs to ten different suture materials. He used the total amount of cellular reaction around each suture as the standard for comparison and showed that polyamide seemed to evoke the least reaction. Stainless steel wire and other synthetic sutures were similar in their behaviour. Silk and silicone treated silk were the least favourable.

Urbaniak et al (1973) studied the effect of knotting on the strength of various suture materials. They showed that knotting a suture reduced the tensile strength of steel by 13% of Tevdek by 48%, Mersilene by 39% and Nylon by 24%. Both before and after knotting stainless steel was approximately three times stronger than Nylon, with Tevdek and Mersilene being in between. All of the materials they tested showed an almost linear increase in strength of suture relative to number of strands tested .

Nystrom and Holmlund (1983) showed that selection of suture material suited to the repair technique used is a factor to consider when performing flexor tendon repair. They showed that the Bunnell criss cross type of suture was particularly prone to gap formation when a flexible suture such as Nylon was used. This tendency was much less with Bunnell suture when a more rigid stainless steel was employed. Both steel and Nylon seemed to be equally effective in resistance to gap formation with the commonly used Kessler technique.

From this review we can conclude that very little work has been done from the mechanical material viewpoint for repair of flexor tendon. This thesis will examine the role of suture materials in tendon repair from mechanical, material, surgical and biological aspects with particular emphasis on the possibility of introducing more recent suture materials into this field.

The new Davis and Geck products are of interest. The synthetic absorbable with high tensile strength and slow dissolution rate in vivo (polytrimethylene carbonate, Maxon), and the non absorbable polymer suture which has enhanced elastic elongation and recovery characteristics (polybutester, Novafil).

1.3 Flexor tendon adhesions

The frequent incidence of poor digital function following flexor tendon repair has stimulated a new interest in determining factors associated with the formation of flexor tendon adhesions.

For many years, the concept has prevailed that the gliding between the tendon and sheath was not maintained after injury. It was thought that the ingrowth of adhesions to the repair site was a natural requirement for external cellular support in order for tendon healing to take place. Potenza (1963) showed that the synovial layer of the sheath was not restored until day 21 after tendon repairs that were totally immobilised. Even at 128 days, blood vessels between the tendon and sheath were in communication by adhesions. However, it was shown later that vascularization of tendon within the sheath is based upon a delicate vincular system, and preservation of as much as possible of this segmental vascular supply is essential for preservation of blood supply to the tendon. (Smith, 1965; Peacock, 1964).

Lundborg (1976), in an ingenious study of isolated flexor tendon segments transferred to synovial fluid of the knee joint, concluded that flexor tendons had an intrinsic repair capability and were not dependent upon extrinsic adhesion formation for healing.

Matthews and Richards (1976) performed an experiment that helped to better define the factors responsible for the formation of adhesions. They noted that the tendon injury itself was not the sole stimulus for the development of adhesions. When flexor tendon were severed, the ends retracted and become rounded, lying freely within the sheath. Similarly, immobilisation of a cut and sutured tendon did not itself lead to an adhesive response from the digital

sheath. However, excision of synovial sheath around the repair site followed by immobilisation frequently resulted in an adhesive response that appeared to contribute to the repair of the defect, overwhelming any intrinsic activity.

Gelbermann and associates (1980,1981,1982) suggested that early motion may enable tendon healing to progress independent of adhesion ingrowth. This concept was based upon the existence of an intrinsic tendon healing capacity supported by synovial fluid nutrition and existing intratendinous vascularity. The functional activity of the epitenon and endotenon, described by Lindsay and Thomson (1960) was significantly increased by protected early motion.

Adhesion formation appeared to be an inflammatory response stimulated by trauma to the tendon (Potenza, 1963; Bunnell, 1918), tendon sheath (Lister, 1983), gap formation (Ketchum et al., 1977; Lindsay, 1960; Seradge, 1983) and total immobilisation. Of these factors associated with adhesions, immobilisation has had the most extensive experimental and clinical investigation.

Gelbermann and Menon (1980), in an experimental study of tendon healing in dogs, demonstrated that the repair process of mobilised tendons differed considerably from that of the immobilised tendons. They showed that early passive digital motion led to an increased tensile strength of repair evaluated between three to twelve weeks, increased range of motion of involved digit, early restoration of tendon gliding surface and suppression of adhesions.

Strickland and Glogovac (1980) compared the immediate mobilisation with more traditional initial immobilisation for three weeks. Protected early

motion was carried out with the dorsal extension blocking splint. Manual passive motion, permitting nearly full interphalangeal joint extension, was performed twice a day for four and half weeks. A wrist cuff and rubber bands were then attached to the finger nails. Gentle passive extension and flexion were then allowed. Unprotected motion was begun at five and half weeks. Of those patients managed by early passive mobilisation, 56% had good or excellent results and 28% were in the poor category. The immobilised group had no excellent results and only 12% were in the good category. 60% were considered poor. The author concluded that early passive motion was an adhesion limiting technique. Duran (1975) achieved an average of 80% of normal active motion with a similar passive motion technique.

Lister et al (1977) reported good and excellent results with different methods. Controlled passive motion was begun immediately after tendon repair. The wrist and MCP joint were positioned in 20 degrees of flexion and DIP joint in 10 degrees of flexion. A rubber band was attached to the nail of the involved fingers. Patients were allowed to actively extend to extension block against the resistance of the rubber band. These were poor or fair results.

These techniques of early motion are generally favoured by hand surgeons today. The reasons for the success of these techniques are not completely clear. There are two possibilities;

1) Motion may act merely to break adhesions mechanically as they form. This possibility was supported by Duran (1975), which showed that limited extension motion, 3 to 5 mm, is sufficient to prevent adhesion formation between the repaired tendons and the the digital sheath.

2) It is also possible that motion has a beneficial effect on tenocytes nutrition, metabolism or both. Additional studies should help to identify those parameters most important in maximising tenocyte healing capacity.

Experimental and clinical studies suggested that restoration of the gliding surface of a tendon may be formed from an early stage by limited motion, resulting in a repair that is mechanically stronger, functionally superior and structurally closer to the normal tendon than the result achieved in the immobilised repaired tendon.

Although it has been shown that early motion may eliminate adhesion formation, there are, however, many factors yet to be investigated which may also influence adhesion formation. This thesis examines the effect of absorbable and non absorbable suture material and vincular blood supply on adhesion formation. Until factors contributing to adhesions are more clearly defined, obtaining the continuity of tendon bundles and the restoration of the gliding surface will remain an inexact science.

1.4 Flexor tendon softening

It might be expected that the strength of the repair site in a cut tendon would increase as time passes, due to tendon healing. However, this is not the case. Mason and Allen (1941) have shown that at about the fifth to twelfth day after repair, the tendon juncture actually is weaker than it was immediately after repair. The tendon becomes soft in the area of repair (up to 80% strength loss was suggested by Mason and Allen (1941) and 50% suggested by Urbaniak et al., (1973)), and its holding power, the ability to resist the shearing effect of sutures, is decreased. Why? Mason and Allen (1941) suggested that the reason for decrease in suture line strength was that the tendon substance itself becomes softer as part of the healing process. Peacock (1959) has demonstrated that an avascular segment of tendon undergoes cell death and collagen degeneration, resulting in a soft, weak tendon. Bergljung (1970) has shown that certain suture techniques produce a constricting effect on the microcirculation of the tendon in the area of the repair. Ketchum (1977) demonstrated that, irrespective of suture technique, significant tension on the repair produces the same effect.

The exact mechanism causing this phenomenon is not understood, yet the practical consequence is devastating. Attempts at mobilisation are likely to disrupt the repair in the first few days after operation.

Various factors could contribute to softening, such as deleterious tissue reaction to suture materials, interrupting the blood supply, inflammatory changes within tendon as part of healing process. This thesis examines the effect of these factors on softening and correlates histological analysis with mechanical testing.

1.5 Flexor tendon healing

Primary flexor tendon healing occurs both from within and without the tendon itself. For many years it was believed that tendon was an inert, almost avascular structure, whose cells were so specialised and mature that they were incapable of contributing to the healing process. Healing, then, was said to take place by ingrowth of both fibroblasts and capillaries from the paratendinous tissues. It is true that a significant, even a major, part of all tendon healing occurs in this manner. Potenza (1963) demonstrated that tendon is invaded by fibrovascular tissue where the integrity of its structure is broken by sutures. This fibrovascular tissue begins in the digital sheath by the second day after the operation. The fibroblasts invading the tendon creep along the surface and into the juncture of apposition and along the suture lines. The collagen laid down by these fibroblasts is still immature by 28 days, but by 35 days it is mature and by 128 days it is indistinguishable from normal tendon.

Lindsay and Birch (1964) studied tendon healing in rats and found that labelled thymidine, which is incorporated into DNA of actively dividing nuclei, is seen in fibroblasts in the paratendinous tissue before any is found in the tendon itself. With time, the labelled thymidine decreased in the paratendinous tissue and increased in tendon, demonstrating indirectly that fibroblasts migrate from the paratendinous tissue to the tendon. This aspect of tendon healing process can not be denied and it is certainly an important contributory factor, as are the capillaries, which first bring in the oxygen necessary for cell survival and which themselves are co-substrates for the proline hydroxylation part of collagen synthesis; and which deliver inflammatory cells to remove foreign materials, such as sutures; and, finally, which bring the amino acid building blocks for protein synthesis.

The above process occurs in the form of a mass migration with large number of inflammatory cells, capillaries, and fibroblasts, and subsequent secretion of collagen. The massive reaction overshadows the response of tendon itself, and it was not until the tendon could be isolated from that response that it could be shown that the tendon has the intrinsic potential to contribute to its own healing.

Lindsay and Thomson (1960) isolated segments of profundus tendon free in their sheath. One of the conclusions from their work, done in chickens, was that an experimental tendon suture zone can be effectively isolated from the perisheath tissues, and the repair process will progress at the same rate as when the perisheath tissues are intact.

Birdsell and Tustanoff (1966) demonstrated an increased uptake of proline, injected at a distance from the wound but found within newly formed collagen in free tendon segments isolated within a tendon sheath. This indicates that the cells of the isolated tendon segment were not just surviving while nourished by synovial fluid, but building protein.

Lundborg and Rank (1978) removed rabbit tendons from their sheaths, divided and repaired them, and placed them in knee joints of rabbits for varying periods of time, then studied them histologically and by electronmicroscopy and made tensile strength measurements on them after the suture were removed. In this tissue culture in-situ experiment, they found that the cells of the tendon survived, except for those in the centre ; the epitenon and endotenon become hyperplastic; the juncture was bridged and resisted rupture with substantial force. The fibroblasts in the epitenon and endotenon secreted collagen, as seen by electronmicroscopy. Lundborg's work did not

exclude the possibilities that cells from the synovium possibly could have seeded into the repair. The results of Lundborg's experiment were also challenged theoretically and experimentally by Potenza and Hertz (1982) and Chow et al (1983) who demonstrated in a similar "insitu tissue culture" model using dog and rabbit that extrinsic synovial cells seeded into the tendon and served as a source of healing cells.

Manske and associates (1984) and Gelbermann (1984) demonstrated the intrinsic capacity of monkey, rabbit, chicken, and dog flexor tendon segments to participate in the repair process up to 12 weeks in tissue cultural media. Cellular migration at the cut tendon end as well as the laceration site was demonstrated. The epitenon layer of cells initiated the repair process by proliferating and migrating into the laceration site. These cells appeared to have a phagocytic function, as they removed cellular debris and collagen fragments. Collagen synthesis appeared to be a function of the cells in the central endotenon core of the tendon. Viability of tendon segments was maintained for up to 12 weeks, and central necrosis was not evident.

Peacock (1959) isolated canine flexor tendon segments from both blood supply and synovial nourishment, by enveloping them with polythene sheets. In two weeks, although the longitudinal strength still was good, he showed that fibres literally fell apart when subjected to criss cross stress and that sutures pulled through the bundles with ease, so that a repair would be weak at that time. At three weeks there was complete avascularity and collagenous disintegration. A tendon segment totally isolated from nourishment underwent cell death and collagen lysis.

To survive and function tendon cells participating in the healing process must

have nutrition from either synovial fluid or blood supply. What is the importance of the blood supply when considering the principles and results of tendon healing? In answering this question, it must be determined first what the blood supply to the tendon in zone II is and what the effects are of interfering with that blood supply.

1.6 Flexor tendon blood supply

Kolliker (1852) concluded from histological study that tendons have no blood supply. Berkenbush (1887) and Arai (1907) were the first to describe the blood supply to flexor tendons of the fingers. They perfused fresh cadavers using "Berlin Ink". Their findings were quite remarkable in light of present concept of vascular anatomy of the flexor tendon and can be summarised as follows:

1) The flexor tendon received vascularization from three sources, namely, the point of osseous insertion, the vessels in the palm and the vinculae to the tendon. Although few investigators consider the function of the vinculae to be only a mechanical supporting structure of the tendon as the name implies (Latin vinculum, a fetter) most anatomists recognised the role of the vinculae as vascular lines to the tendons.

2) Both superficialis and profundus tendons were consistently noted to have focal areas of avascularity located just proximal to the chiasma a of camper on the flexor superficialis and more distally on the profundus tendon between the vinculum longum and the osseous insertion.

3) Most vessels remained on the surface , but a few entered the substance of the adult tendon. All vessels ended in loops without forming a network of capillaries.

Mayer (1916) also studied the flexor tendons of the foot and observed the same results previously noted by Berkenbush and Arai. Mayer also discovered the focal ares of avascularity and noted that they were on the frictional surface

(i.e. the volar surface) of the tendon.

Edwards (1946) gave a detailed picture of the vascular system in laboratory animals and in man after injecting Indian ink at constant pressure. He showed blood vessels running a longitudinal course along the tendons. Edwards also emphasised the sparsity of the intrinsic blood supply to the flexor tendons, which was sufficient only to meet the minimal needs of the proportionately few tenocytes.

Brockis (1953) injected fifty amputated fingers with colloidal silver iodide. He confirmed that flexor digitorum profundus had longitudinal vessels and was reinforced by small vessels from the vinculae.

The effect of blood supply on tendon healing has been observed experimentally and clinically. Peacock (1964) stated that tendons without their segmental vascularity undergo necrosis and replacement with scar tissue. Smith (1965) indicated that tendon metabolism cannot be maintained through a fluid medium alone but the vascular circulation of the tendon was essential for survival. Verdan (1972) recognised that results following repair of both superficialis and profundus tendons were better than when the superficialis tendon was excised and only the profundus tendon was repaired. This clinical observation was soon supported by investigative studies. Leffert and Weiss (1974) attributed this clinical finding to the vulnerability of the profundus tendon's circulation following excision of the superficialis tendon. Their injection studies demonstrated an integral association between the vinculum brevis to the superficialis tendon and vinculum longum to the profundus tendon. Banes et al (1981), in chickens, showed that vincular injury decreased the metabolic response of tendon and impaired the healing ability.

Matthews and Richards (1976) demonstrated that hypovascular rabbit tendons are much more likely to form adhesions than those in which vascularity is preserved. The reason for this difference is not clear. There are certainly alternate routes of tendon nutrition, and in many studies the synovial route has actually appeared to be the predominant one (Potenza, 1963; Manske, Whiteside and Lesker, 1978; Manske and Lesker, 1982; McDowell and Snyder, 1977). The efficiency of synovial diffusion, however, is dependent on at least three factors. One is motion, which promotes the "milking" action apparently necessary to pump synovial fluid within the tendon substance; the second is the integrity of the synovial sheath; and the third is the permeability of whatever medium exists between the synovial membrane and tendon surface to the nutrients present in synovial fluid. Postoperative haematoma, immobilisation, and motion limited by the pain may all impair these qualities and thus render the nutritional inflow delivered by the vincular or intrinsic blood supply relatively more important. Under such a circumstance, it seems logical that blood supply impairment might be the final blow.

The blood supply of the tendon has proven to be a factor of importance when considering the results of tendon healing. Therefore, accurate knowledge of the vascular system of the tendon is of practical value in tendon operations. No intravital study of the microcirculation of the flexor tendons of the chicken's toe can be found in the literature, even though the chicken is often chosen as an experimental model for the repair of the flexor tendons: This thesis investigates the normal vascular anatomy of the chicken's flexor tendons within the sheath and also determines the vascular and avascular zones.

Chapter 2: A comparison of the structural and functional anatomy of human finger flexor tendons with the chicken flexor tendon system

2.0 Introduction

The digital flexor tendon of the chicken's foot was first chosen by Lindsay and Thomson (1960) as a model for flexor tendon studies. Since then other investigators (Ashley et al, 1964; Kessler and Nissim,1969; Manske and Lesker, 1982) have used this model, because all the important functions and structures of the human finger are present in the chicken toe. In this chapter, the main similarity and differences between the flexor tendons, pulleys, sheaths, vinculae, and vascular structures of the chicken and human finger are described. Such information will be useful in designing tendon experiments and interpreting results. The structural and functional study is restricted to the third digit, the largest and therefore the most suitable model for experiment.

2.1. Flexor tendon system

The digital portions of the flexors in the chicken toe and in the human finger are shown in in figure 2.1. The flexor apparatus of the chicken's third toe includes three tendons. The flexor perforatus, the flexor perforatus et perforans, and the flexor profundus or perforans. The flexor perforatus is the most superficial of the tendons. It bifurcates in the middle part of the proximal phalanx just prior to insertion. Both the perforatus et perforans and profundus tendons pass through this bifurcation. The flexor perforatus et perforans bifurcates at the distal portion of the second phalanx, inserting at the lateral and medial aspects of the phalanx. The distal portion of the flexor perforatus et perforans is widened, covering the flexor profundus. The flexor profundus emerges through the bifurcation of the perforatus et perforans and inserts into the base of the fourth phalanx, on its ventral aspect (Koch, 1973).

The human finger has only two flexor tendons, the superficialis and profundus. The superficialis bifurcates at the distal portion of the proximal phalanx, inserting at the lateral and medial aspects of the base of the second phalanx. The profundus tendon emerges through this bifurcation and inserts into the base of the distal phalanx, on its ventral aspect.

The flexor digitorum profundus, in both the chicken and human, flexes the distal phalanx, after flexor digitorum superficialis has flexed the middle phalanx. The flexor digitorum superficialis flexes first the middle and then the proximal phalanges.

The chicken digital flexor tendon mechanism can be assessed clinically better than that of the most experimental animals. Its foot action is similar to that of the human finger in that its primary action is prehensile, although it is associated with weight bearing and the degree of closure is not as complex or as fine as that of the human finger.

A comparison of the anatomy of the human tendon with the chicken flexor tendon system

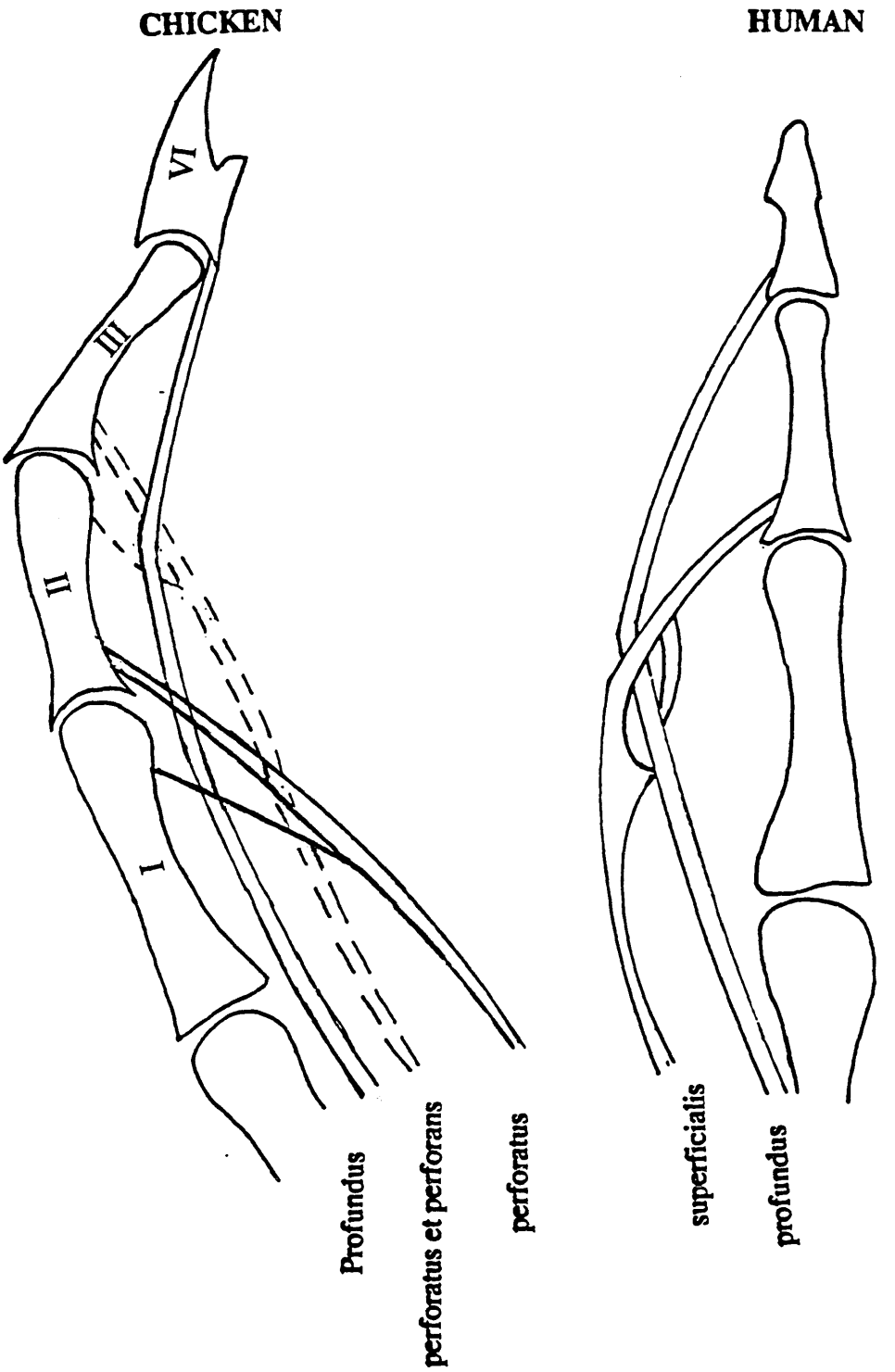


Fig 2.1: The structural anatomy of human finger flexor tendons and chicken digital flexor tendon.

2.2 Flexor tendon sheath system

The three flexor tendons of the chickens third toe and two flexor tendons of the human finger are surrounded by a thin elastic connective tissue membrane, the common tendon sheath, from the insertion point of the profundus up to the palm.

The tendon sheath in both the human and the chicken is attached to the periosteum of the terminal parts of the phalanges and to the fibrous capsule of the joints on the volar aspect of the digit. In the middle portion of the phalanges this connection is quite loose. The space closed by tendon sheath is bridged over by a number of fine tissue formations connecting the walls of the sheath with the tendons.

The inner surface of the tendon sheath, in both the human and the chicken, is covered by tenosynovial membrane, the surface of which is flat and smooth. The gliding of the tendon is facilitated by the synovial fluid, a lubricant secreted by the tenosynovial membrane. The papillary formations of the membrane in chickens are believed to be the areas of synovial fluid secretion (Conway et al., 1970). It is believed that the localisation of the papillary formations in the vicinity of the interphalangeal joints is due to the natural folds of the tenosynovial membrane which helps to adjust the tendon sheath to the required position (Jones and Amis, 1988) . The papillary outgrowths also possibly function as ball bearing during the gliding motions of the flexor profundus(see fig 2.2).

The digital tendon sheath has three functions:

1) It allows for smooth gliding of its contained tendinous structures in flexion and extension.

2) It serves a nutritive function in providing a contained bursal environment for synovial fluid.

3) It holds the tendon close to the bones, i.e. maintains geometry, prevents bowstringing.

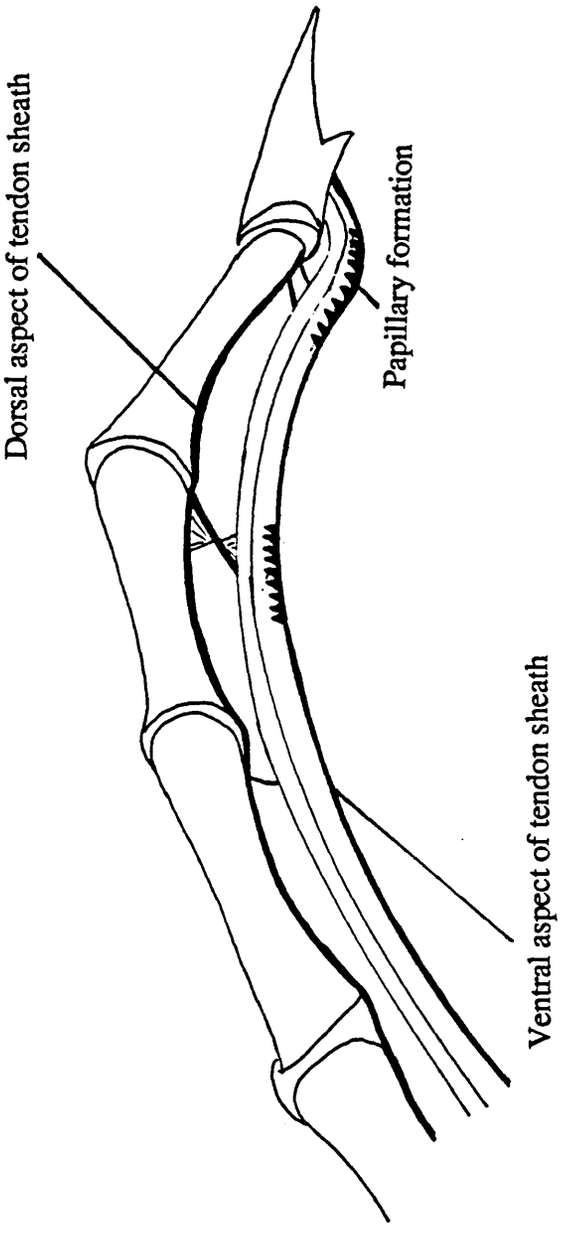


Fig 2.2: The sheath of the flexor tendons and the location of the papillary formations(Chicken)

2.3 Flexor tendon pulley system

In both the chicken and human digit the tendon sheath has thickenings called pulleys. The systems of pulleys in the chicken's third toe and the human finger are shown in fig 2.3.

In the chicken there are two pulleys (Koch, 1973). The first pulley A1 arises from the volar aspects of the proximal half of the first phalanx and A2 from the volar aspect of the proximal half of the second phalanx. The pulley system in the human, described by Doyle and Blythe (1975), is a series of annular and cruciform thickenings of the sheath. The annular pulleys are composed of relatively thick, inflexible bands of transversely oriented fibres, whereas the cruciform pulleys, overlaying each joint between the annular pulleys, are thin, membranous, and flexible and are therefore able to expand and contract with the motion. The important A2 and A4 pulleys overlying the proximal and middle phalanges attach directly to the bone and are critical to repair and reconstruction (Lister, 1979; Kleinert et al., 1981). The A1 and A3 pulleys are near the joint axis. A review of biomechanics and anatomy of this system indicated that the closer the pulleys were to the joints, the more effective they were in producing joint motion for a given amount of active tendon excursion (Doyle and Blythe, 1975).

Annular pulleys in both the human and chicken are of biomechanical importance in preventing tendon bowstringing during digital flexion (Hunter, 1984; Idler and Strickland, 1984).

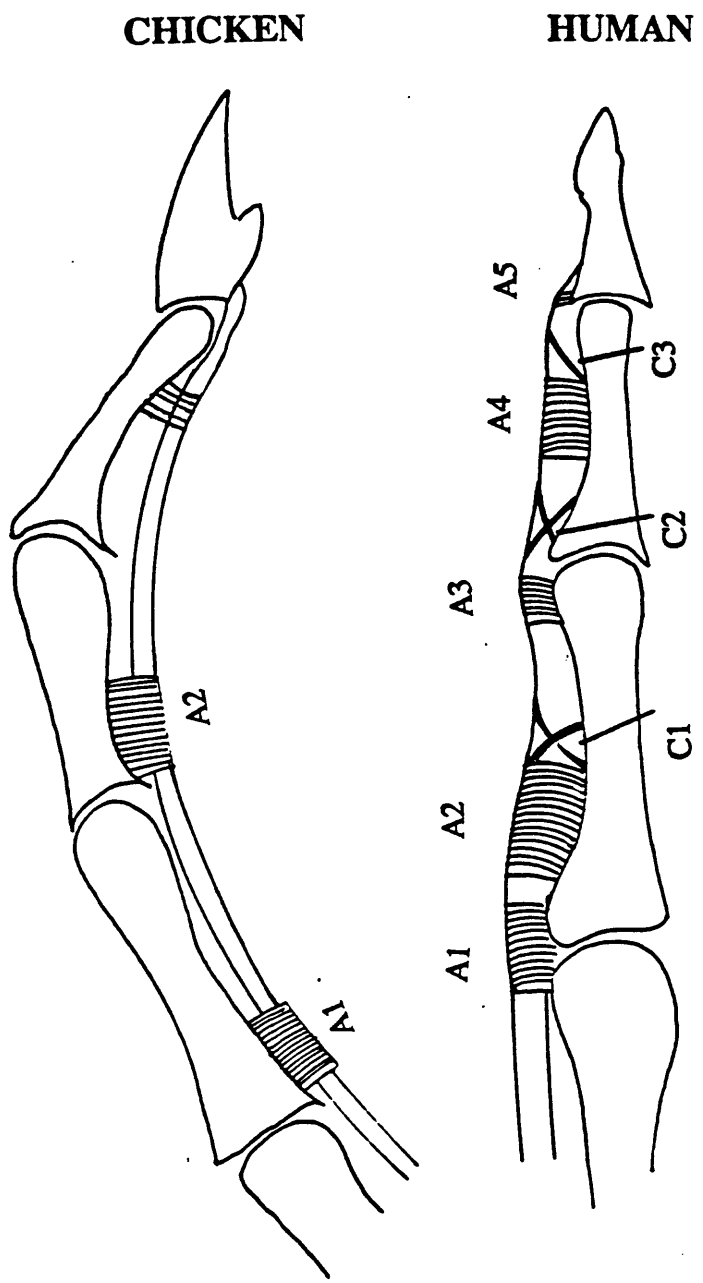


Fig 2.3: The system of pulleys in the chicken's third toe and the human

2.4 Flexor tendon vincular system

In two areas of the digital canal the tissue connections (the vinculae) between the tendons and the tenosynovial membrane are thicker. The location of the vinculae in the chicken's third toe and in the human finger can be observed in fig 2.4. In both the human and the chicken digits there are short and long vinculae.

The chicken third toe has two short vinculae. One is a continuation of the volar articular plate of the third interphalangeal joint; it runs horizontal to the digit in the rest position. The other, slightly larger, is 2 mm proximal to the previous one and connects the tendon with the third phalanx and is oblique in position. The vinculum longum is a fine elastic tissue which inserts into the palmar surface of the distal end of the second phalanx and is situated parallel to the tendon.

The vinculum like structure that inserts into the superficialis tendon and through which the profundus tendon passes, is shown in fig 2.4.

In the human finger there are also two short vinculae. One vinculum is found at the insertion of the flexor profundus tendon into the distal phalanx and the other short vinculum runs between the synovial wall of the proximal phalanx and the two tendons. The long vinculum is represented also by two types: One group unites the tendon near the mid line; the other group unites the superficialis tendon with the periphery of the synovial wall. Beckham et al. (1975) showed that the vinculae in the chickens have much longer and more complex structures than in men. He stated that vinculae certainly contain vessels which supply the tendon within the sheath, but these vessels make up only a very small portion of the total mass; most of the structure consists of collagen and elastic fibres.

The primary function of the vinculae in both the human and chicken is to carry the blood supply to the tendon within the tendon sheath, but the short vinculae may allow the tendon to have some direct action on phalanges proximal to their insertion (Hollinshead, 1965).

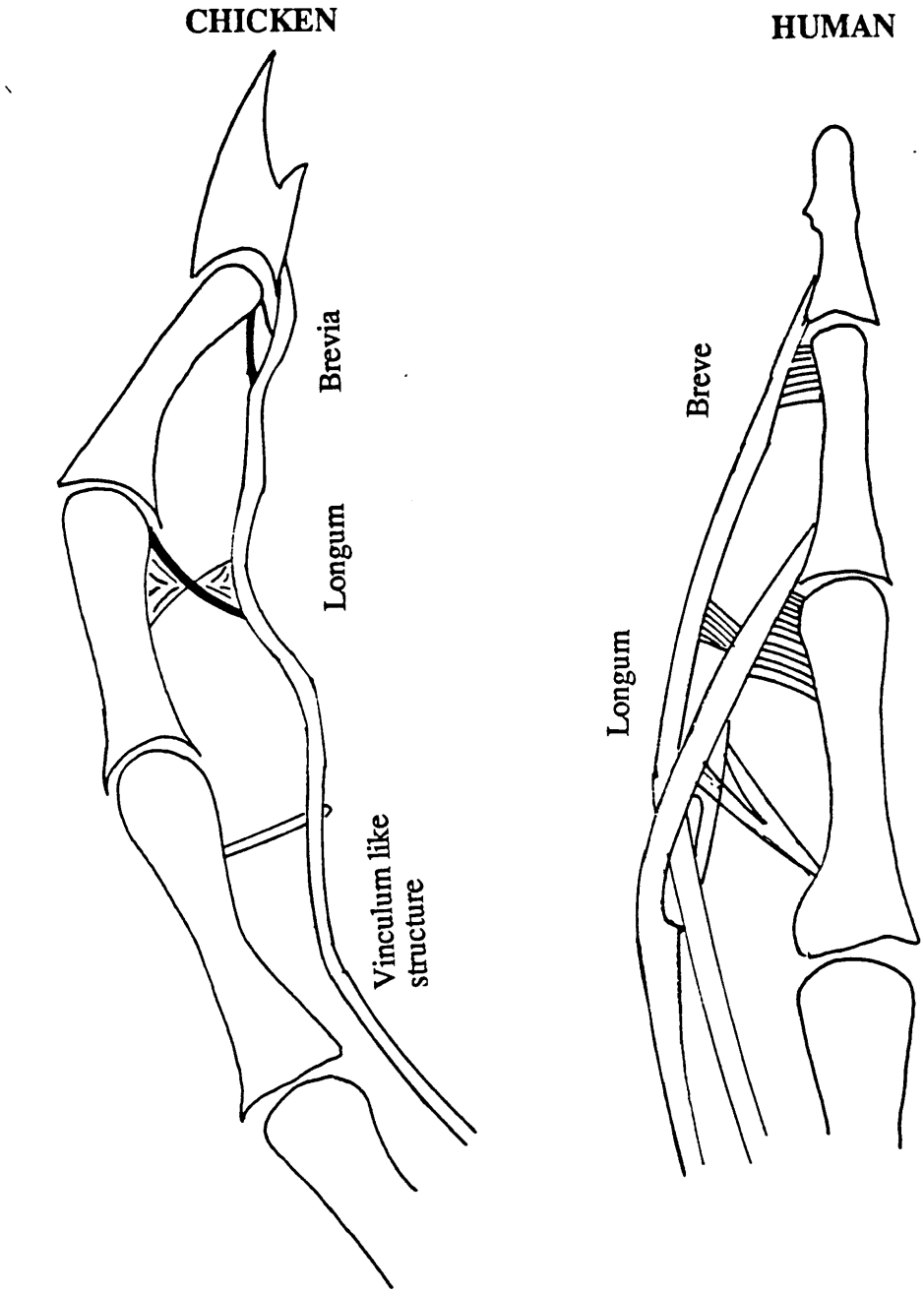


Fig 2.4: The location of vinculae in the chicken's third toe and in the human finger

2.5 Investigation of the vascular anatomy of the flexor tendons.

The vascular supply of tendon was proven to be an important factor when considering the principles and results of tendon healing (see chapter 1). No intravital study of the microcirculation of the flexor tendons of the chicken can be found in the literature, even though the chicken is often chosen as an experimental model. The purpose of this study was to investigate the normal vascular anatomy of the chicken's flexor profundus tendons and to find out whether there are vascular and avascular zones similar to those found in human fingers.

2.5.1 Methods and materials

Indian ink and barium sulphate perfusions were carried out on 8 chickens. Six chickens were perfused with barium sulphate and two with the Indian ink. A general anaesthetic was administered, consisting of Halothane, oxygen and nitrous oxide. The animal was laid supine and a butterfly cannula was inserted into a wing vein, so that 2000 units of Heparine could be given just prior to cannulation of the heart. The left ventricle of the heart was chosen as the most suitable part for introduction of the cannula. In order to enter the base of the heart a lateral incision was carried out up to the second ribs. The heart was exposed and the pericardium was removed. The heart was cannulated using a polythene cannula with a smooth bevelled tip (8 FG) .

2.5.1.1 Barium sulphate perfusion

The perfusate (barium sulphate 100%w/v and 10% gelatin) was led from the flask via a rubber tube near to its base and was drawn into a 20 ml syringe through a three way tap. All air bubbles were expelled and the three way tap was connected to the cannula into which the blood had been allowed to reflux.

20 ml of the perfusate was manually perfused into the heart at a constant pressure over a period of 4-5 minutes. This was repeated until 'bleeding micropaque' was observed in a small incision made on the dorsum of the foot. Between 80 and 120 ml of perfusate was usually required.

The animal was finally sacrificed under general anaesthesia by an intravenous injection of 5 ml Euthatal (sodium thiopentone). The heart was ligated to prevent reflux of the perfusate and the specimen was placed in the deep freeze at a temperature of - 25 degrees Celsius for 24 hours to solidify the perfusate.

2.5.1.2 Indian ink perfusion

Indian ink injections were carried out using commercial Indian ink diluted in normal saline in the ratio of 1:5 and then filtered three times through filter paper. The rest of the procedure was carried out as described in section 2.5.1.1. Perfusion was done under hand control until the capillary bed filled with injection fluid.

2.5.1.3 Preparation of the specimen

The feet were amputated from metatarsal phalangeal joint. The skin was removed and the specimen was fixed in 10% phosphate buffered formal saline for three weeks. The specimen was then decalcified by immersing in 35% formic acid for a further three weeks when it was returned to formal saline solution.

The decalcified specimen was now prepared by removing the subcutaneous tissue, tendon sheath, perforatus et perforans and perforatus tendons under the operating microscope. Care was taken not to touch the most superficial glistening layer of the profundus tendon (i.e. the epitenon). The tendon was now connected to the bone by means of the vinculae and its ordinary distal insertion.

2.5.1.4 Radiographic examination

Mammography X-ray

The decalcified specimen of whole tendon while connected to the bone was then x-rayed using a Hilger Watt x-ray machine (see fig 2.5) and fine grain mammography film without a screen (Kodak Min -Rx-ray film). A Dean D44 overcouch x-ray unit with a Dynamax HD 500 x-ray tube was set to give a 6 second exposure at 200 mA and 40 kv at the focus to film distance of 50 cm and using a 1 mm focal spot. The film was processed in an Agfa Gevaermatic 60 automatic desktop processor. This mammography film was the negative that subsequently provided enlarged photographic prints to demonstrate the vascular pattern of the whole tendon. By this method a whole specimen could be seen in one film, but a good resolution of blood supply in the tendon can not be observed. To achieve this the profundus tendon was excised from its connection points (i.e. point of insertion and vinculae) and x-rayed as described below.

Microfocal Radiography

Microfocal x-rays were now taken of small pieces of the tendon using a Philips table top x-ray generator (PW 1720) (See fig 2.6). This apparatus had a small focal spot and produced high resolution images as a result of its small penumbra. The x-ray film used was Kodak high resolution film (ESTAR thick Base) SO 343, which has microfine granularity and ultra - high resolving power giving extremely high contrast.

Both film and specimen were loaded into a light proof circular metal cartridge, which, when attached to the X-ray generator, was orientated in the vertical plane. Special precautions were taken to prevent both contamination

of the film by formalin from the specimen, and relative movement between the specimen and film during exposure. The film was separated from the specimen within the cartridge by means of a clean dry polythene disc that provided a radiolucent barrier, impermeable to formalin, thus protecting the emulsion of the film. A black disc of thicker polythene provided an airtight and light proof seal to the cartridge so that when a vacuum was applied to the assembly, the film and specimen were then held in apposition, even when turned vertically.

Fixed parameters of 40 kV and 25 mA were used throughout, but the exposure time was varied according to the thickness of the specimen. It was determined that an exposure time of 3 minutes was suitable for the thinner specimens and 5 minutes for thicker specimens. The film was developed in a thermostatically controlled, agitated water bath for 3 minutes at 20 degrees centigrade and fixed for 4 minutes. It was washed in running tap water for half an hour, rinsed in distilled water and dried in the heated cabinet.

The microradiographs thus obtained enabled the vascular pattern in the tendon to be demonstrated.

The microradiograph of the perfused tendon served as a negative. It was placed into the cassette of a de Vere photographic enlarger with a Cooke Aviar 8.5 inches focal length lens, and the image was projected onto photographic paper. Prints of the vascular pattern of the tendon at 10x magnification were obtained.

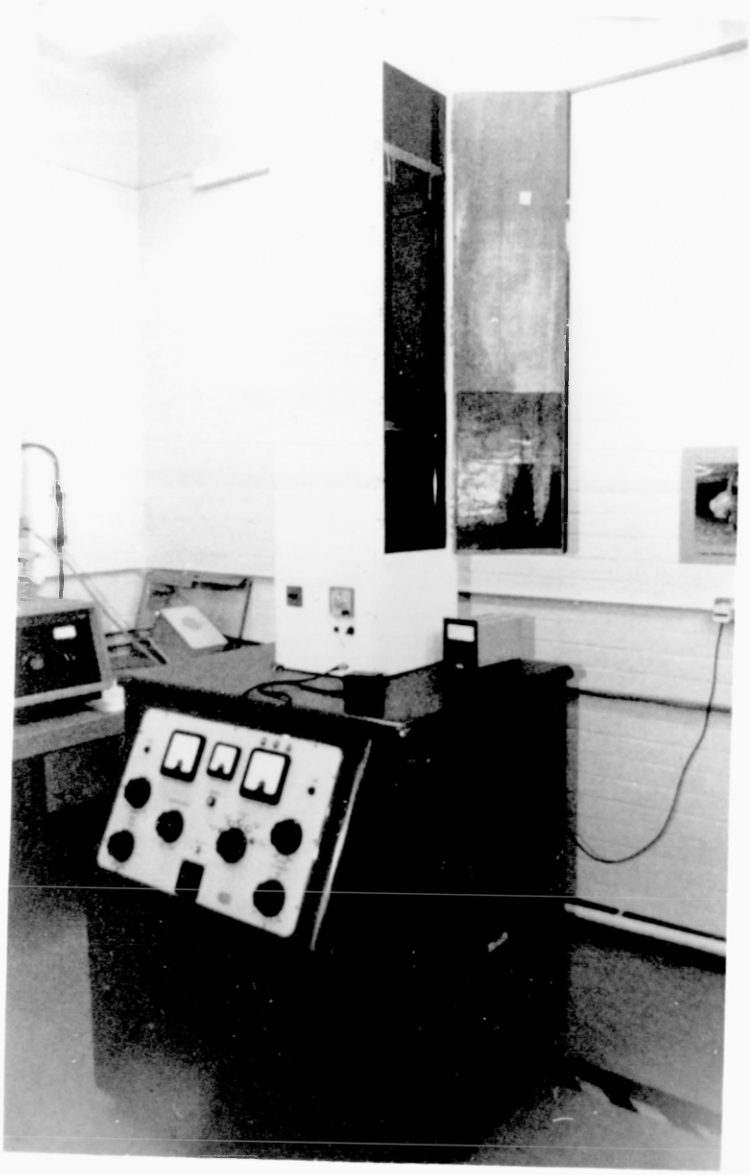


Fig 2.5: Hilger Watt x-ray unit machine

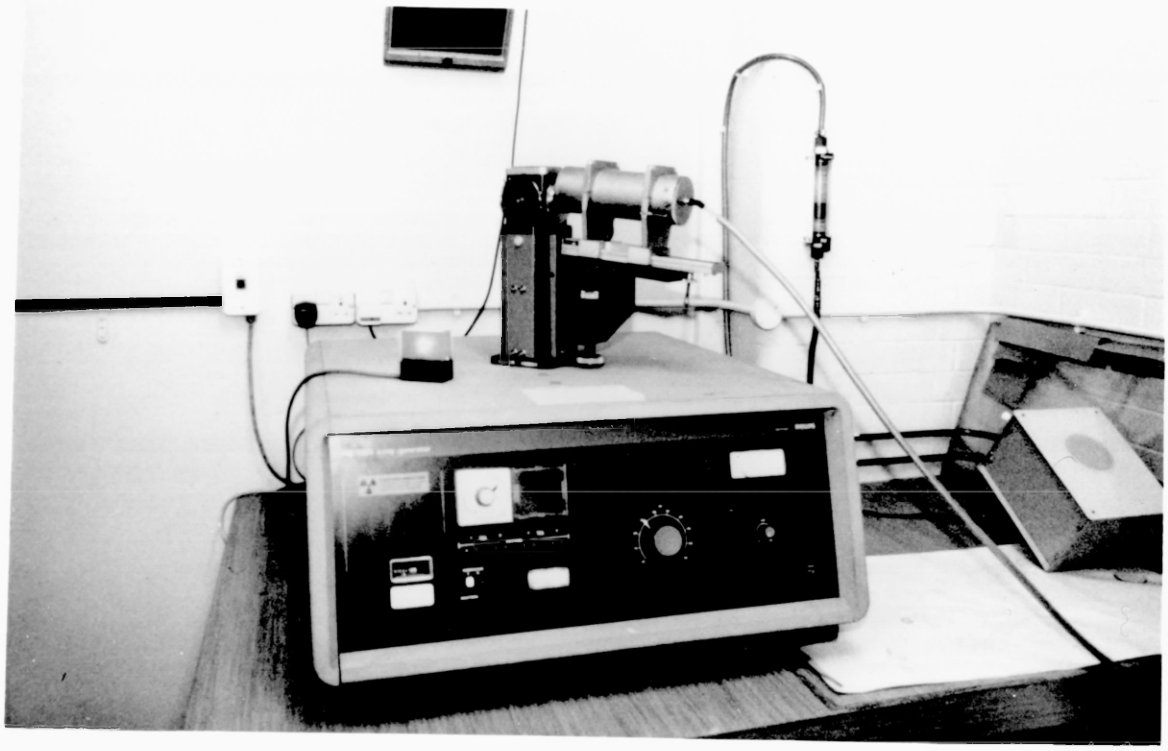


Fig 2.6: Focal x-ray unit machine

2.5.1.5 Processing of the Indian ink perfused material

Once decalcified the specimens were dehydrated in ascending grades of alcohol and then in:

a) 1:1 mixture of absolute alcohol: ether for 24 hours

b) 2% celloidin in a 1:1 mixture of absolute alcohol : ether for 5-7 days

c) 4% celloidin in a 1:1 mixture of absolute alcohol : ether for 5-7 days

d) 8% celloidin in a 1:1 mixture of absolute alcohol : ether for 3-4 days

Embedding took place in an airtight container in which the specimens were orientated in plastic trays containing 8% celloidin solution. A small quantity of ether was placed in the bottom of the bell jar container to allow bubbles to rise up before the celloidin hardened at the surface. The specimens were then exposed to air for one hour each day until a firm skin was formed on the surface (this normally required three weeks).

The celloidin blocks were mounted onto wooden cubes and stored in 79% alcohol until cut. A sledge microtome was used to cut thick 250 micron sections which were mounted onto gelatin coated slides with a quantity of Canada balsam /turpentine solution. These slides were allowed to dry for three weeks.

The slides were photographed using a Wild Heerbrugg photomicroscope (M400) which incorporated an automatic exposure meter.

2.5.2 Results

Both Indian ink and barium sulphate perfusions were suitable methods for demonstration of tendon vascular architecture .

The lack of uniformity in microvascular architecture in different tendons was striking. Fig 2.7 shows the intermediate part of profundus tendon from

different animals showing an entirely different arrangement of the microvascular pattern.

However, on larger scale, the results showed that the flexor profundus tendon of chicken's third toe contained three well defined segmental vascular systems of different origin. The proximal system originated from the vinculum like structure at the middle part of the first phalanx (see fig 2.8a). An intermediate system originated from the vinculum longum at the distal end of the third phalanx (see fig 2.8b). Here, the dorsal part of tendon contained longitudinal vessels sending vertical loops into the tendon substance. The distal system originated from the vinculum brevis at the tendon insertion (see fig 2.8c) . This system consisted mainly of the longitudinal vessels but some vertical loops were also identified. The tendon did not contain vessels originating from within the bone. Between the major sources of the blood supply were zones of apparent avascularity tending to be opposite the joints. Vascular and avascular zones were also confirmed with Indian ink perfusion (see fig 2.9). The vessels of vinculum longum and brevis, fold up in an accordion like fashion (fig 2.10) in flexion.



Fig 2.7: Middle segments of the chicken profundus tendon: observe the differences in the architectural arrangement.

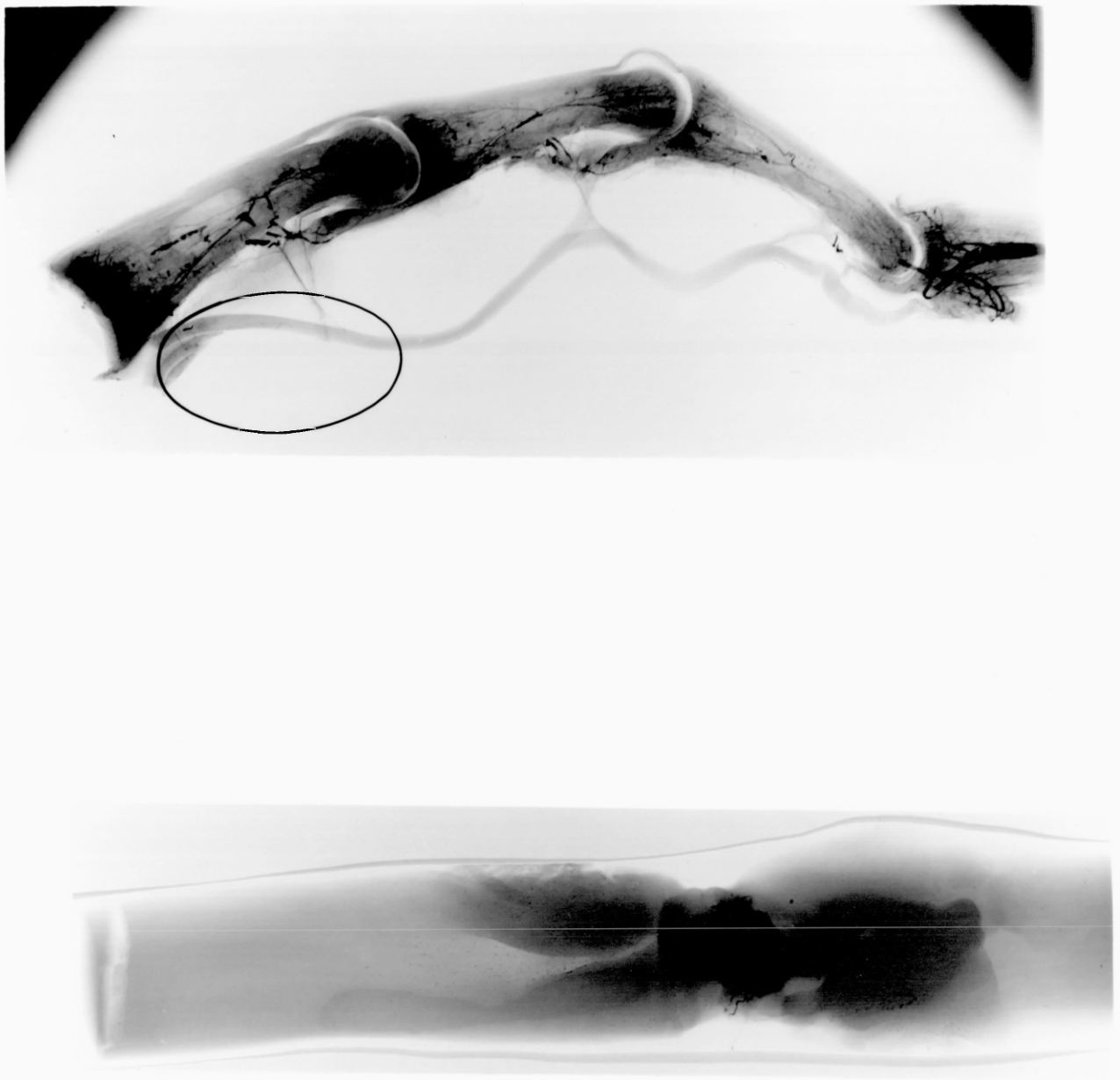


Fig 2.8a: The proximal vascular and avascular zones in Flexor digitorum profundus of chicken's third toe (Barium sulphate perfusion). Observation area is indicated by ring in the inset.

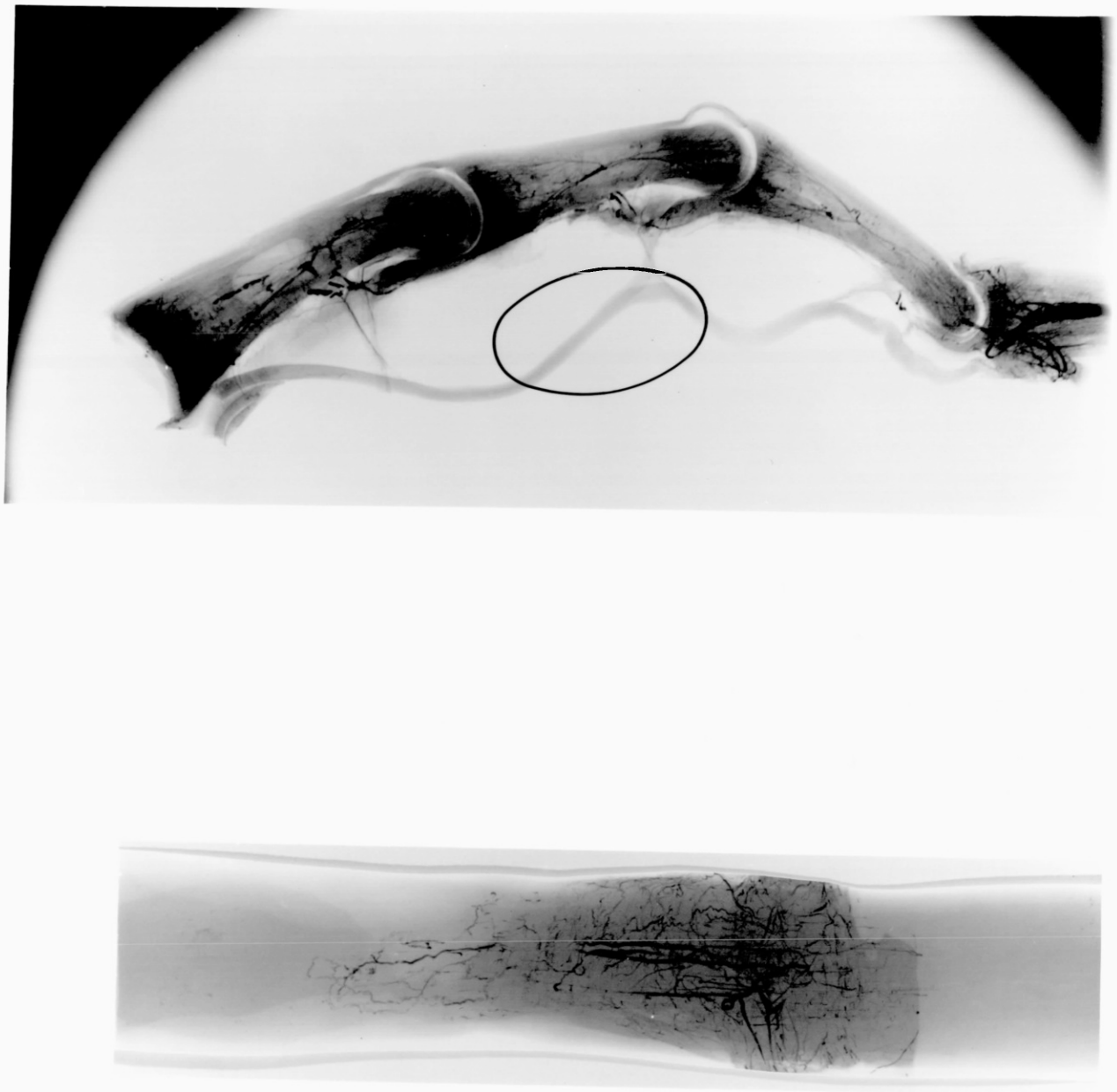


Fig 2.8b: The intermediate vascular and avascular zones in flexor digitorum profundus of chicken's third toe (Barium sulphate perfusion). Observation area is indicated by ring in the inset.

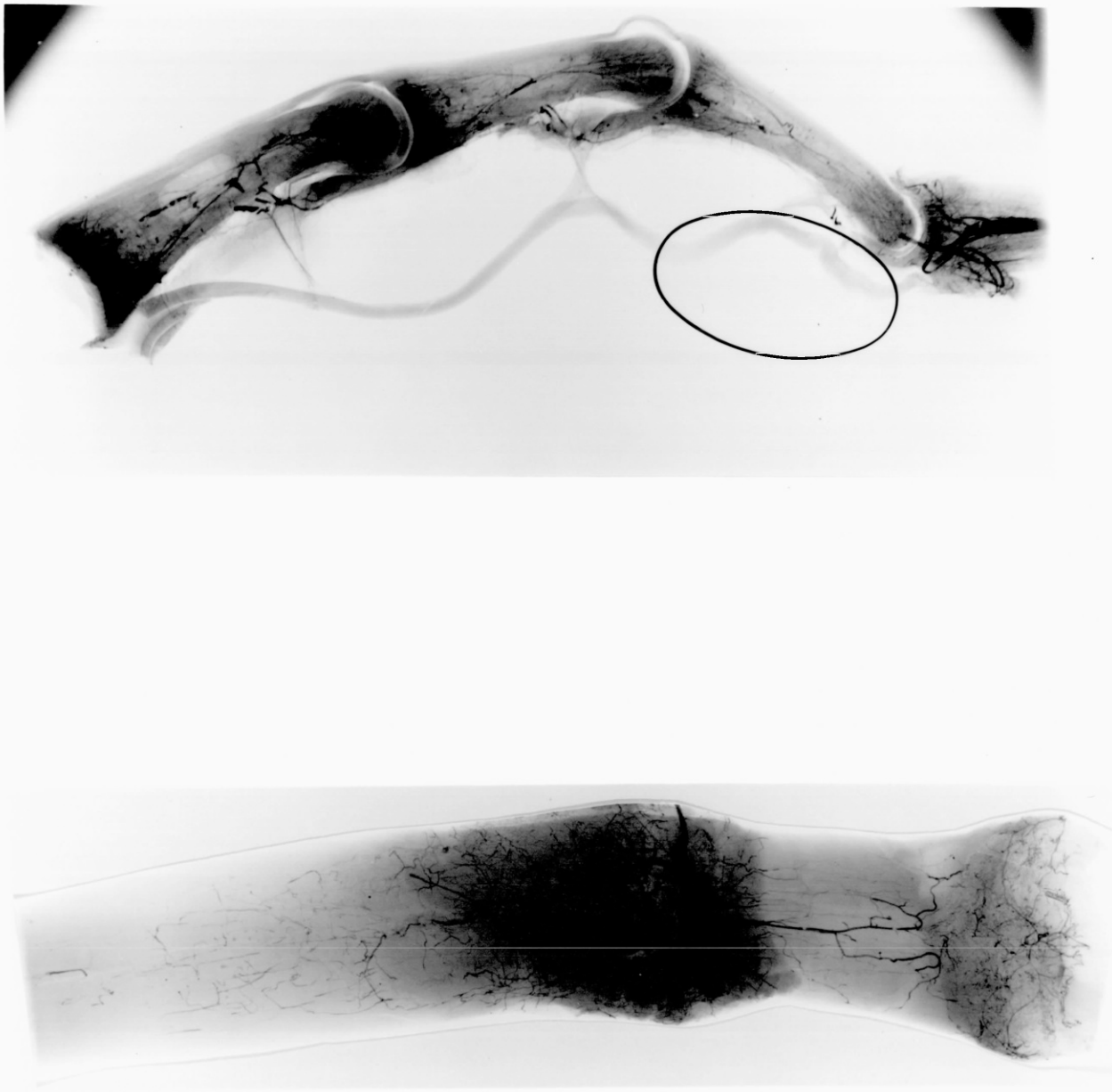


Fig 2.8c: The distal vascular and avascular zone in flexor digitorum profundus of chicken's third toe (Barium sulphate perfusion). Observation area is indicated by ring in the inset.

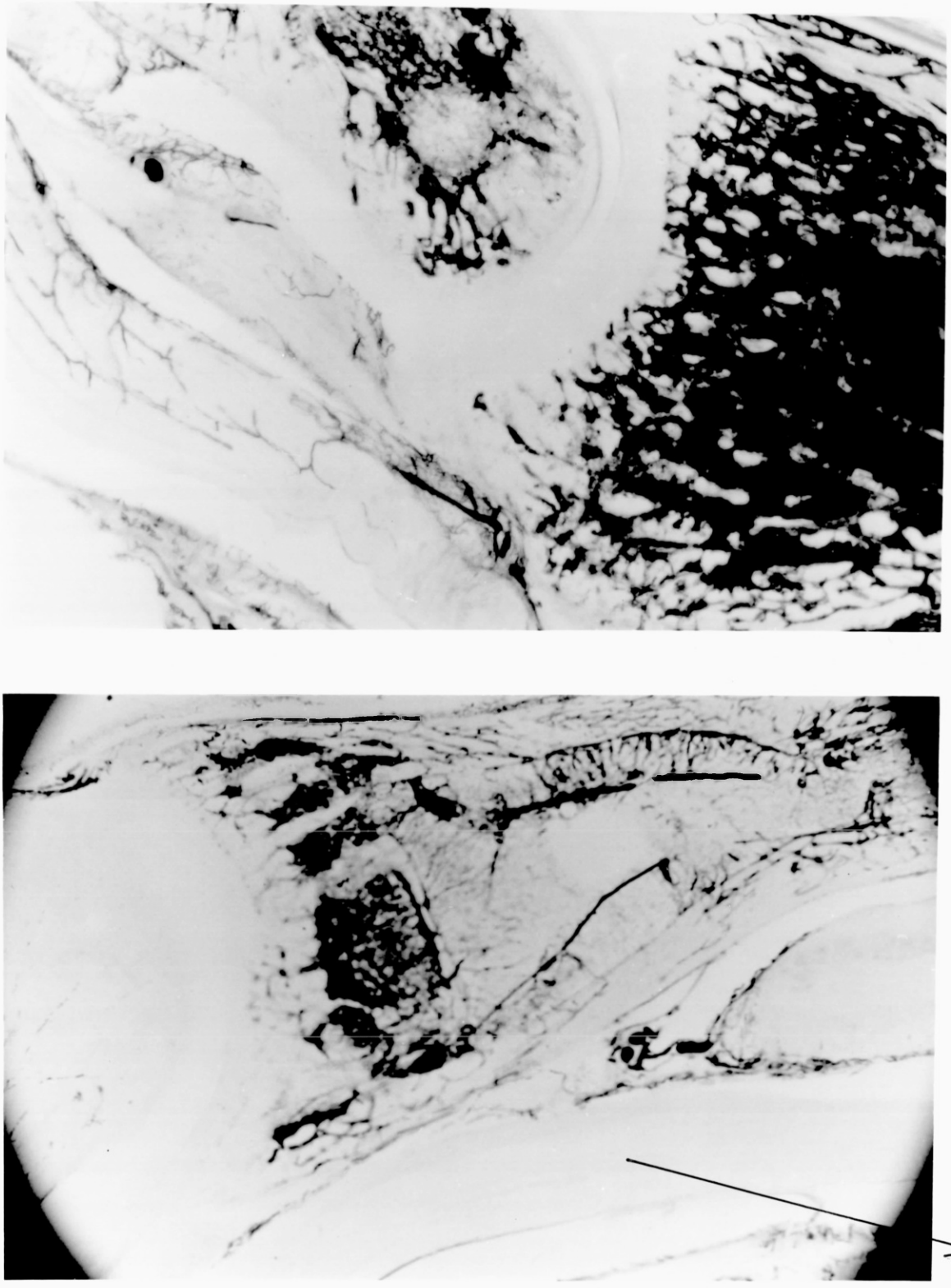
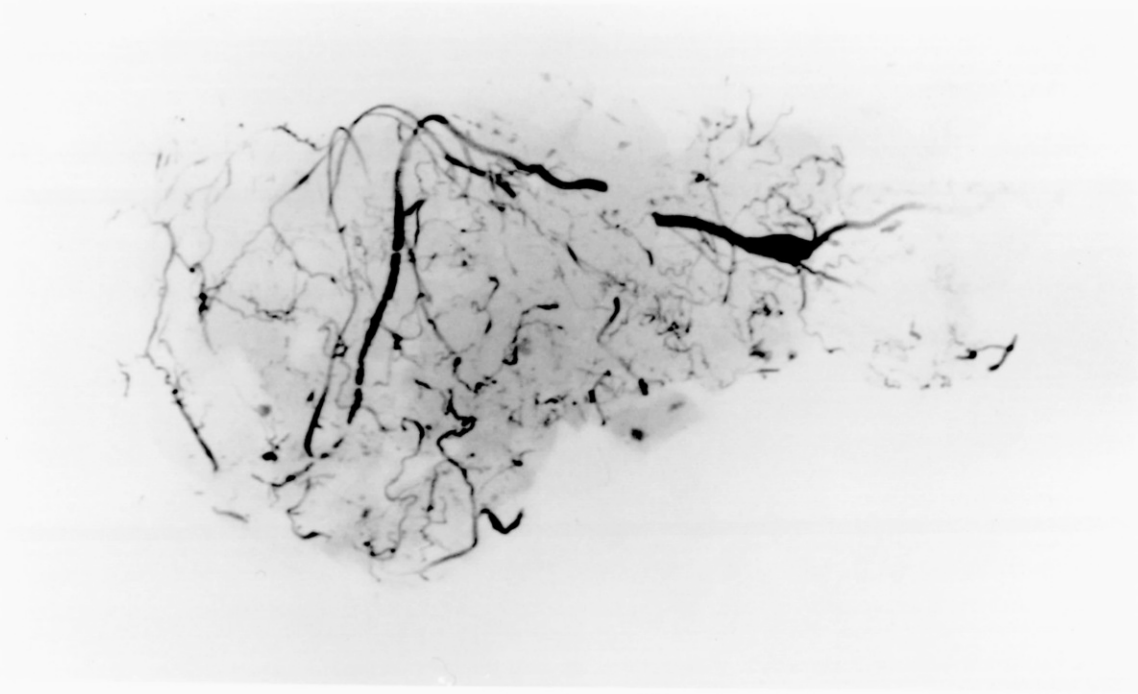


Fig 2.9: The vascular and avascular zone using Indian ink perfusion (Distal part of the flexor digitorum profundus).

Longum



Brevis

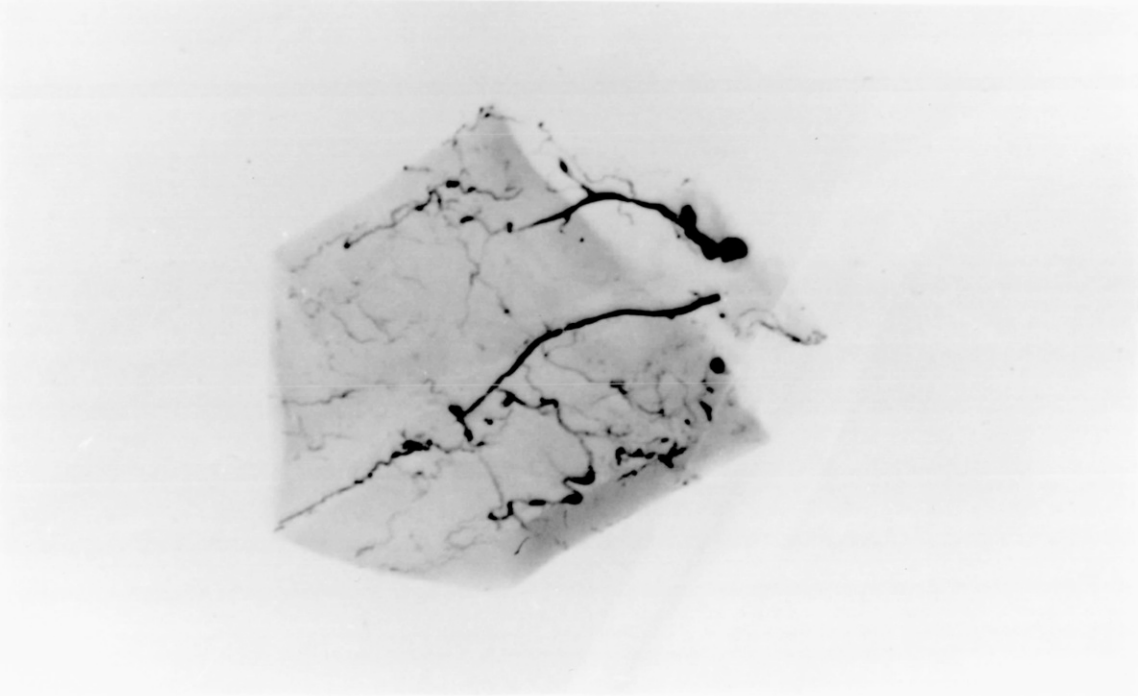


Fig 2.10: The vessels of the vinculum longum and brevis (Transverse sectio
20x Magnification)

2.5.3 Discussion

The vascular anatomy of the third toe of the chicken conforms to the general pattern observed in man. (see fig 2.11).

Exact knowledge of the vascular and avascular zones is important when considering tendon healing. Matthews and Richards (1976) demonstrated that hypovascular tendons are much more likely to form adhesions than those in which the vascularity was preserved. Manske et al (1978) reported that synovial fluid provides the major nutritional source for the flexor tendon. Manske and Lesker(1982) demonstrated that the nutritional source is not constant throughout the digital sheath and that the vascular supply to the tendon offered a second system of nutrition, by perfusion. The effect of this system was most evident in the distal tendon segment. Caplin et al. (1975) stated that if the lacerated site is in the poor or avascular zone, the tendon heals slowly, and requires 6 to 8 weeks of controlled mobilisation, whereas in the vascularized zone controlled mobilisation is only needed for 3 to 5 weeks and the tendon heals much quicker. However, most of the previous investigators who used the chicken as a model did not specify the location of the lacerated site and reported various results. It seems that placing sutures in vascular or avascular zones may have caused variations in results between previous studies.

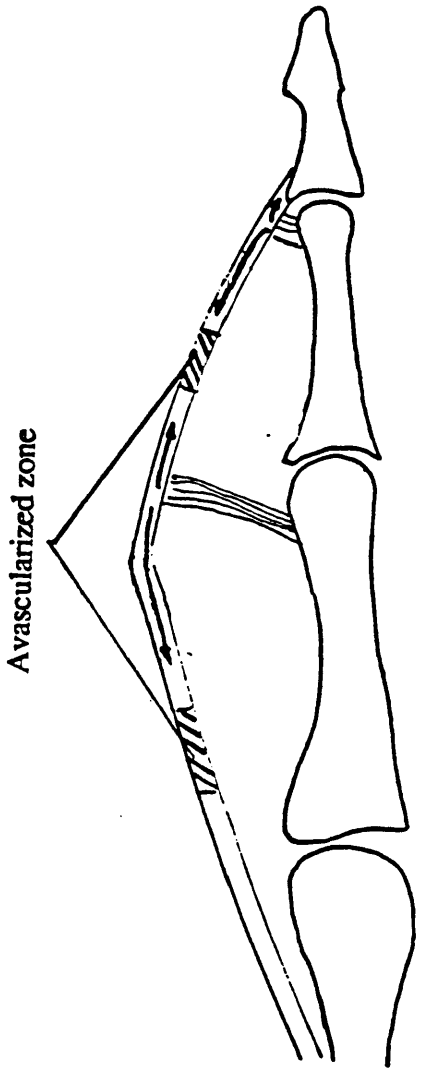


Fig 2.11: The main vascular supply of the flexor digitorum profundus tendon in the human. There are 3 vascular systems of different origin. The proximal system originates from nutrient vessels in the proximal synovial reflexion and from the longitudinal intrinsic vessels from the palm region. An intermediate system originates from the vinculum longum at the PIP joint level. A distal vascular system originates from the vinculum brevis. The avascularized zones between these systms are indicated by shaded area.

Chapter 3: Laboratory study to design an improved suture technique

3.0 Introduction

The repair of severed flexor tendons within Verdan's zone II (1979) of the fingers continues to be a challenge to surgeons. Satisfactory results are not always achieved and poor results, characterised by inability to move the fingers due to adhesions, have been reported in 20% of cases even in specialist centres (Lister et al., 1977; Kleinert et al., 1981). Probably due to this fact, many suturing configurations have been proposed for primary repair of flexor tendon in attempts to improve the results. (Mason & Allen, 1941; Bunnell, 1956; Ketchum et al., 1977; Verdan, 1979; Savage, 1985). Matthews and Richards (1976) suggested that the method of suturing flexor tendons may affect their healing potential, and therefore the clinical results of the repair. However, attention has mostly been focussed on trying to design suturing methods which are strong enough to allow early mobilisation (Kessler and Nissim, 1969) while also trying to avoid constricting the blood supply. Progress has been made by trial and error rather than by trying to identify the fundamental reason why particular suture techniques are good or not.

The aim of this chapter is to investigate in some detail the features of suturing techniques which influence their holding power. This could relate to the following factors :

1) Suture materials:
a) Strength of absorbable and non absorbable suture material with regard to gap formation and ultimate strength.

2) Peripheral stitches:

b) Strength of different peripheral stitch techniques used in tendon repair

c) Strength of sutures in different layers such as epitenon or within tendon fibres

3) Core stitches

d) Effect of the locking loops on the strength of the suture technique and mechanism of failure of such loops

e) Effect of criss cross configuration on the strength of suture technique and mechanism of failure of such criss cross.

Finally the knowledge gained from the above mechanical tests will help us to design an improved suture method.

3.1 Strength of absorbable and non absorbable suture material immediately after tendon repair with regard to gap formation and ultimate strength.

The purpose of this section is to examine the strength of absorbable and non absorbable suture material immediately after flexor tendon repair and recommend the most suitable suture material for tendon suturing.

3.1.1 Methods and materials

The following 4-0 suture materials were tested to establish the most suitable materials and data base line.

Polytrimethylene(Maxon) carbonate	Absorbable	Monofilament	Davis and Geck
Polydioxanone (PDS)	Absorbable	Monofilament	Ethicon
Stainless steel	Non-absorbable	Multifilament	Ethicon
Polypropylene (Prolene)	Non-absorbable	Monofilament	Ethicon
Polyester (Ethibond)	Non-absorbable	Multifilament	Ethicon
Polybutester (Novafil)	Non-absorbable	Monofilament	Davis and Geck

3.1.2 Tensile testing of suture material

Fifteen examples of each suture material were tested for the ultimate strength and break elongation using an Instron material tensile testing machine(Model 1122). This device consisted of a pair of clamps to hold the specimen, a displacement transducer, a load cell coupled to the upper clamp, an amplifier, and an integral graph plotter which drew a tensile test diagram representing the relationship between the load and movement of the clamps. The clamps had flat surfaces with a diamond knurled finish and were operated by screws. Adequate clamping of the specimens into the tensile testing machine was important. The evaluation of the results should not be troubled by slipping of the specimens or breaking in the clamp jaw. The tests were rejected if these occurred. It was assumed that specimen slippage in the clamp was negligible under load, so that clamp movement was taken to be the specimens elongation. The distance between the jaws was constant throughout the experiments (50 mm). All the tests were conducted in air at the crosshead speed of 50 mm/min. The specimens were subjected to a single strand unknotted pull.

3.1.3 Tensile testing of the sutured tendon

Each suture material was then applied to finger flexor tendon. The tendons were removed from human cadavers, males and females, between the ages of 63-81 years, within 24 hours of death. The tendons appeared to stay "fresh" during this period and showed no significant changes in water content, since they were in their normal surroundings. These tendons were then sealed in polyethylene bags containing Ringer's solution and deep frozen prior to use. Deep freezing of the tendon has been employed quite frequently without evident changes in mechanical properties. The tendons were subsequently thawed by immersing them under physiological saline for not longer than 5

minutes, as it would results in swelling and hence subsequent changes in mechanical properties. These include large deformation at failure and higher failure energy (Viidik, 1966). The specimens were transected and the cut ends sutured together, using microsurgical instruments and 4X magnification loupes. Accurate insertion would be difficult without magnification. The modified Kessler core stitch technique, without peripheral stitches, was applied. The longitudinal component of the Kessler technique must pass deep to the transverse part of the suture, or it will not grasp or lock onto the tendon fibres (Pennington, 1979). The transverse pass of the suture passed across the tendons 10 mm from the cut surface and the suture was secured by a knot between the tendon ends. This was laid down as a double tied first throw followed by two single half hitches. The sutures were knotted with proper tension that avoided bunching or an accordion effect (too tight) or separation of the site of approximation (too loose). Each suture material was applied to 15 separate tendons and, therefore, a total of 90 repairs were studied. The sutured tendon was tested in an Instron tensile testing machine. All the tests were conducted in the air at at room temperature at a crosshead speed of 50 mm/ min. The surfaces of the tendon were kept moist with Ringer's solution at all times during suturing and tensile testing, to avoid mechanical properties changes arising from dehydration. The water content of the tissue is of main importance, since with drying the stiffness increases. Exposure to air causes progressive water loss from the tendon, and loss is greatest in the beginning. This loss decreases when the relative humidity is brought towards 100%; 65% relative humidity at 21 degrees centigrade is sufficient to prevent significant changes in the water content for 10 minutes (Galante 1967).

The force was measured when a 2 mm gap and the ultimate rupture of repair were reached. Gap formation was assessed by eye, using a ruler closely parallel to the tendon. Experience showed that the tendon ends often parted faster on one side, rather than with an equal gap appearing all round the

periphery. It was possible to look at the repair from different directions as the test progressed and take measurements from the side which came apart first. This method is sufficiently accurate for the comparative purposes.

3.1.4 Results and discussion

Testing of suture materials above produced results in line with USP specifications (see table 3.1 and 3.2). Maxon is significantly stronger than PDS and multifilament stainless steel ($p < 0.03$). Since the diameters of these three sutures are similar, the strength superiority of Maxon is intrinsic to the fibre (i.e. this is not yet related to the holding power of the suture within the tendon tissue). Novafil is slightly stronger than Polypropylene and polyester (Ethibond). Since the diameters of these three sutures are also essentially equal, the superiority in the straight pull tensile testing is a reflection of the inherent strength superiority of polybutester strand. Therefore, Maxon and Novafil might be the appropriate choice in comparison with that of the commonly used sutures, polyester, polypropylene, PDS, and stainless steel.

Prolene, Novafil, Maxon and PDS extend by 30-35% of their initial length before rupture, polyester by 25%, multifilament stainless steel hardly stretched at all with the loads up to two-thirds of its ultimate strength, while above this point small increases in load produce rapid elongation. i.e. yielding. It follows that load on steel suture should not be less than two- thirds its breaking strength.

The results of stressing the various suture materials immediately after tendon repair are shown in fig 3.1. Maxon, PDS, and stainless steel produced a good resistance against both gapping and ultimate rupture. There were no significant differences between the Novafil, Prolene and Ethibond in the tendon tissue with regard to gap and rupture producing forces.

Table 3.1: straight pull strength, diameters, and break elongation of suture material used in this experiment

Material	Diameter (mm)	Mean strength±SD (N)	Break elongation %
Polytrimethylene carbonate(Maxon)	0.227	24.5±0.2	27.8
Polydioxanone(PDS)	0.227	20.9±0.10	33.6
Stainless steel	0.200	18.0±0.32	30.0
Polypropylene(prolene)	0.192	13.2±0.01	36.0
Polyester (Ethibond)	0.190	13.0±0.03	27.0
Polybutester (Novafil)	0.182	13.6±0.02	35.0

Table 3.2: straight pull strength, diameters, and break elongation of suture material according to USP specification

Material	Diameter (mm)	Mean strength±SD (N)	Break elongation %
Polytrimethylene carbonate(Maxon)	0.125-0.199	24.3	27.8
Polydioxanone(PDS)	0.125-0.199	20.7	33.6
Stainless steel	0.198-0.210	18.0	30.0
Polypropylene(prolene)	0.155-0.199	13.5	36.0
Polyester(Ethibond)	0.155-0.190	13.0	27.0
Polybutester(Novafil)	0.155-0.199	1.36	35.0

The most striking feature of this work was the rapid formation of a gap between the tendon ends when no peripheral stitch was present. This occurred as soon as a modest pull was applied across the tendon (9 N).
Stainless steel suture was hard to knot, kinked easily, made a bulky knot and cut through the tissues. Although Maxon and PDS were significantly stronger then the other non absorbable suture materials that can be used at the time of the repair, they have the disadvantage of losing strength when they are placed in the tissue. This will be discussed in chapter 5.

Novafil, Ethibond and Prolene are easy to handle, knot easily and securely and glide easily through the tendon and are not springy.
This in vitro study showed that Novafil, Ethibond and Prolene are the most desirable non absorbable suture materials for tendon suturing. The choice of material for tendon repair is therefore, a matter of preference.

The strength and tissue reactivity of Maxon and Novafil in vivo will be examined in chapter 5.

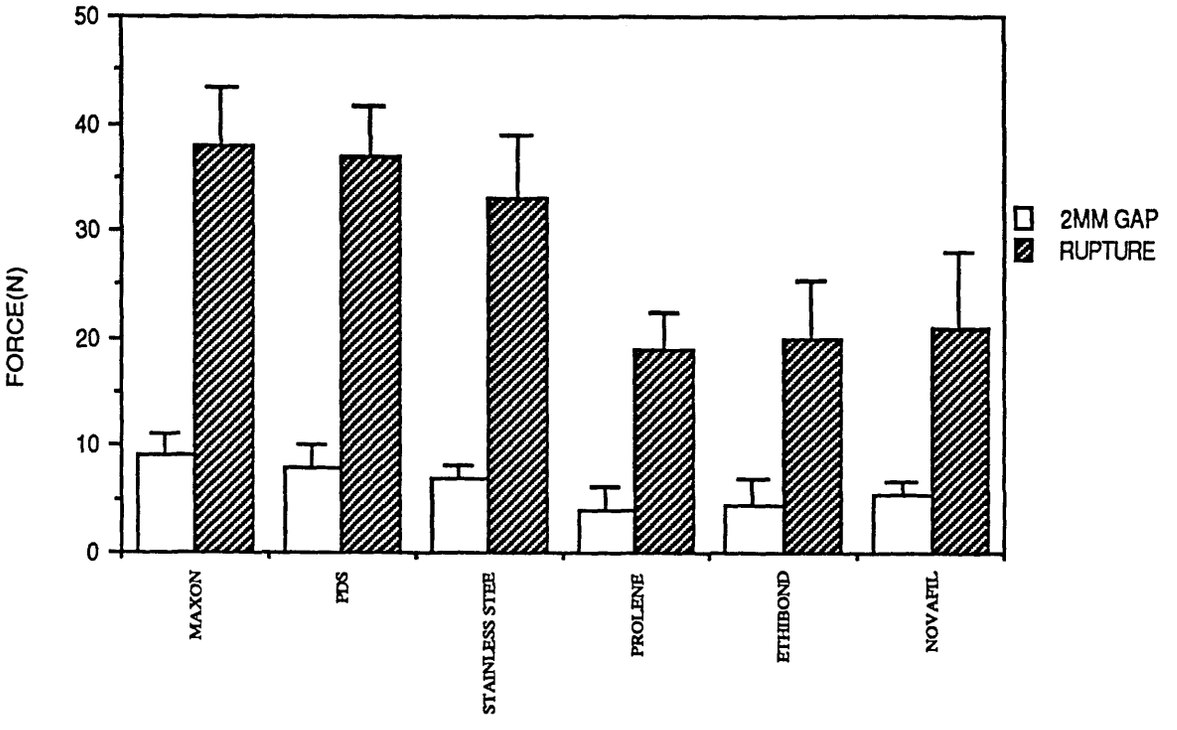


Fig 3.1: Strength of the different suture material in tendon. Mean ± 1 standard deviation. N=15

3.2 Strength of peripheral stitches used in tendon repair

A running circumferential suture is usually used to approximate the margin of tendon ends after placing the core stitch. It was believed that peripheral stitches were only to tidy up the repair, and not to contribute to strength. However, it has been shown that peripheral stitches do contribute to strength (Wade et al, 1986) and delay the onset of gap formation (functional failure point) under load. The aim of this study was to investigate the strength of peripheral stitches used in tendon repair.

3.2.1 Methods and materials

In order to test the immediate strength of different peripheral stitches, fresh digital flexor tendons of approximately equal cross sectional diameter were taken from human cadavers (see also section 3.1.3). The tendons were immediately cut, repaired and tested in an Instron tensile testing machine using 5-0 Ethibond and these seven suture methods: interrupted, interrupted Lembert, interrupted vertical mattress, over and over, interrupted horizontal mattress, interrupted Halsted and continuous Halsted (see fig 1.2). The peripheral stitch was inserted in the epitenon and extended 3 to 5 mm from each cut end. 15 examples of each method were tested and four stitches were applied in each tendon. The forces were measured at which a 1 mm, then 2 mm gap formed, and when the ultimate rupture occurred. The testing conditions were as in section 3.1.3.

3.2.2 Results and discussion

The results from different peripheral techniques have been compared in terms of the force required to produce a 1 mm gap, 2 mm gap, and ultimate rupture.

Figure 3.2a reveals that there was no significant difference between the techniques at 1mm gap, although higher average forces were required for the horizontal mattress technique. However, fig 3.2b indicates that a significantly ($p < 0.05$) larger force is needed to create a 2 mm gap with the continuous Halsted technique than with the over and over technique. Fig 3.2c represents the force necessary to cause rupture and the difference between strength of the stitches was again statistically significant.

Reports in the literature concerning the clinical importance of gap formation between the tendon ends have associated different gap sizes with failure of the procedure. Ketchum et al (1977) suggested that this critical gap is of the order of 1mm or less, whilst Seradge (1983) stated that a gap of up to 3 mm or more is required to cause impairment of the results. The results shown here indicate that determination of the force to cause a 1 mm gap does not allow an effective comparison among the various techniques employed.

At 2 mm gap a larger variation between the forces was observed which could possibly indicate that measurement of forces at this gap is more valid for comparing the techniques. Although the force required to cause rupture is an interesting means for comparison of the strength of the techniques, the gap created prior to reaching the ultimate strength is probably too large for it to be a useful measurement from a clinical point of view.

Continuous suturing of the peripheral stitches was marginally stronger than an interrupted stitch. A continuous stitch distributes the load more evenly because it is difficult to tie individual stitches at the same tension, so they break consecutively as each comes under load at approximately 2 N increments.

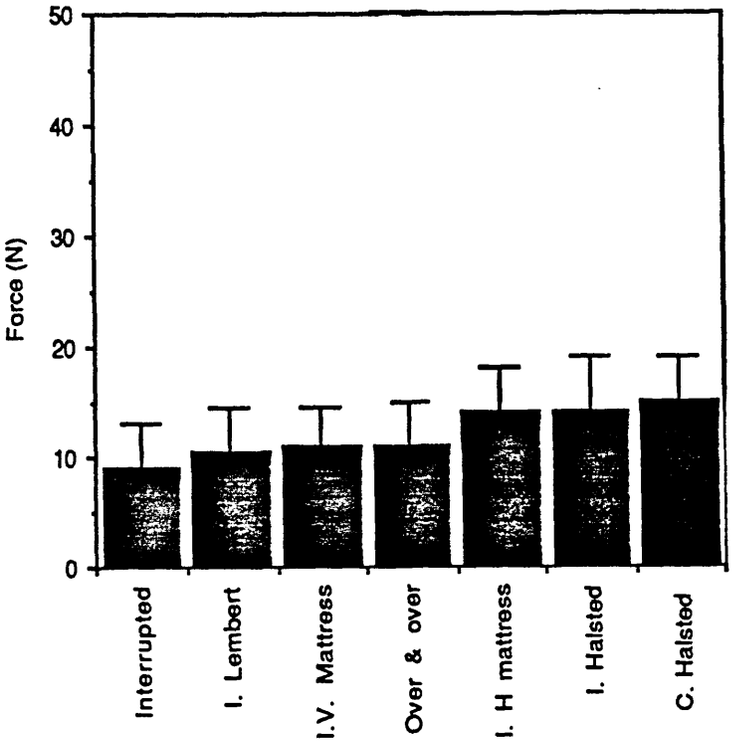


Fig 3.2a : The force necessary to cause 1 mm gap formation with a range of peripheral sutures. Mean ± 1 standard deviation

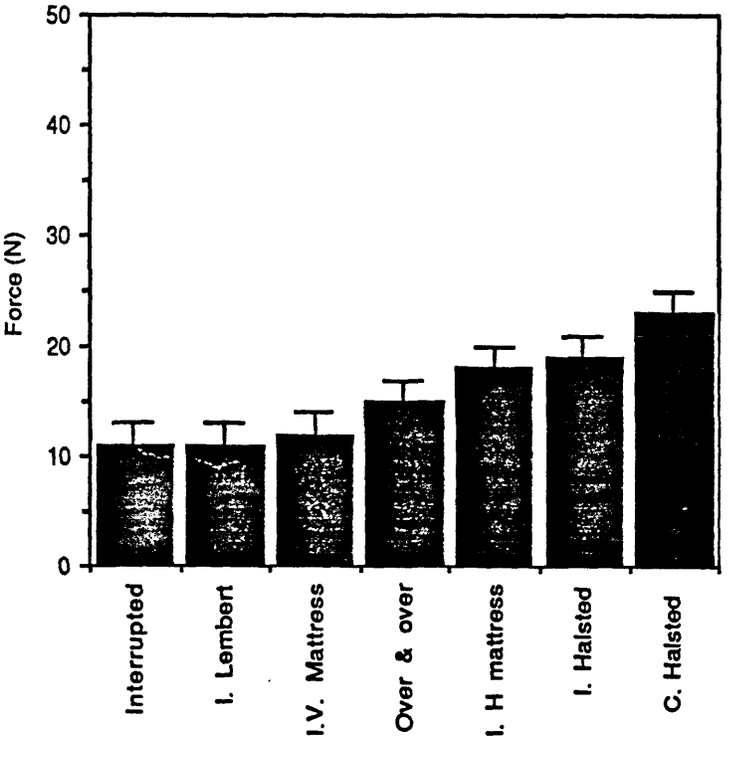


Fig 3.2b : The force necessary to cause 2 mm gap formation with a range of peripheral sutures. Mean ± 1 standard deviation

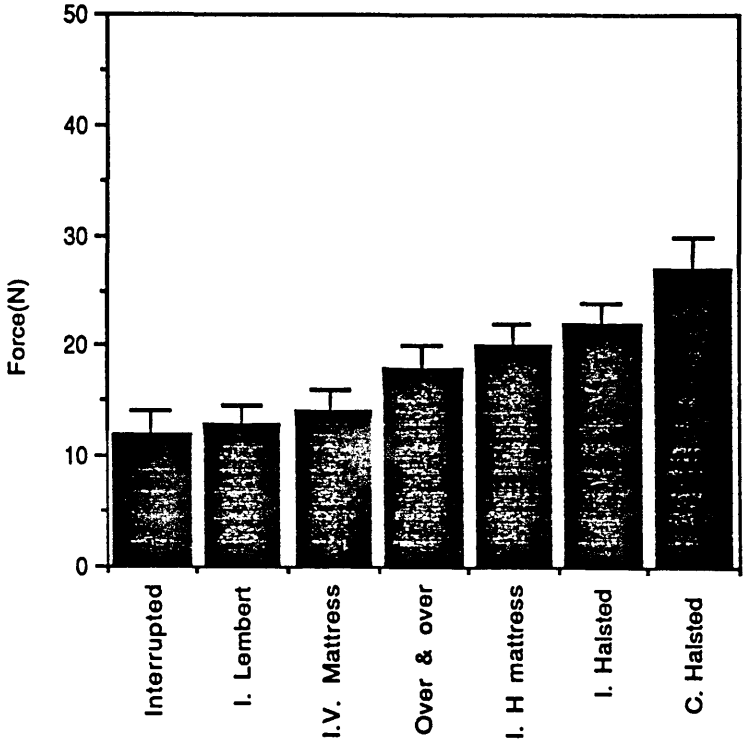


Fig 3.2c : The force necessary to cause rupture with a range of peripheral sutures. Mean $\pm$ 1 standard deviation

The graphs 3.2a. 3.2b, and 3.2c clearly showed that with any type of anastomosis where the pull of the suture is parallel to the collagen bundles gap formation occurs at smaller loads.

This study suggests that the stitches should be continuous and perpendicular to the tendon. Therefore, continuous Halsted is a possible choice. However, this technique leaves a lot of suture material on the surface of the tendon and might cause adhesions later on (Matthews and Richards 1976). This study also showed the importance of peripheral stitches and their contribution to the strength.

3.3 Strength of suture in different layers such as epitenon and within tendon fibres

It has been shown in the section above that the peripheral stitch can contribute to the strength of the suture, but in tendon repair the peripheral stitches are usually placed in the epitenon and not within the tendon fibres, since it is widely believed that would result in eversion of tendon fibres and adhesions or triggering (Lister, 1983). It has not yet been clearly defined whether the grasping strength of the cells in the epitenon and within the tendon fibres are different. The aim of this study is to investigate these differences, to see whether it would be advantageous to place them deeper into tendon.

3.3.1 Methods and materials

In order to find the grasping strength of the epitenon and the tendon fibres mechanical tests were carried out on sutures placed into cadaveric human digital flexor tendons. The tendons were cut into 30 mm lengths, and a 5/0 multifilament stainless steel suture was placed transversely through the epitenon layer of 50 specimens 10 mm from one end. The transverse pass of the suture was fixed at 6 mm length by use of a template gauge. Passing through the fibres was avoided by gradual and controlled motion of the needle just beneath the epitenon layer; thus the needle was visible throughout the passage of the suture. Sutured tendons were tested by extending them until failure in an Instron materials testing machine at a crosshead speed of 50 mm/min in air. A loop of suture wire was mounted in one clamp and the tendon end in the other. The specimens were kept moist with Ringer's solution throughout, to prevent changes due to dehydration. The tests were rejected if the suture broke in the clamp. A 5/0 multifilament stainless steel suture was then placed transversely between the tendon fibres, again taking a

path 6 mm long within the tendon at the same place, and this preparation was tested as before.

In order to correlate histology with mechanical testing, fingers from embalmed cadavers were fixed in 10% neutral formalin for one week. Specimens were decalcified in a solution of 22% formic acid and 20% sodium citrate, dehydrated in graded alcohols, cleared in chloroform, wax embedded, sectioned at 5 micron and stained using Azan trichrome.

3.3.2 Results and discussion

Fig 3.3 shows the results of the grasping strength tests within the tendon fibres and in the epitenon layer. A significant difference between the two different layers ($p < 0.001$, Student's paired t test) was observed: the grasping strength of suture in the tendon fibres was 83% higher than that within the epitenon. All sutures were pulled out of the epitenon, while all those within the tendon fibres ruptured when the force of distraction was increased. These results correlate with histology showing loose epitenon tissue structure and dense tendon fibres (see fig 3.4).

This study suggests that peripheral stitches within tendon fibres will increase the mechanical strength by 80%. A new peripheral stitch based on this finding has been designed (see section 3.6). The design of the new peripheral stitch should place the suture within tendon fibres and avoid eversions, thus improving the results of surgery by avoiding gap formation at the edges of the repair until higher forces are applied, yet still also avoiding problem such as triggering , caused by eversion or bunching of the tendon fibres.

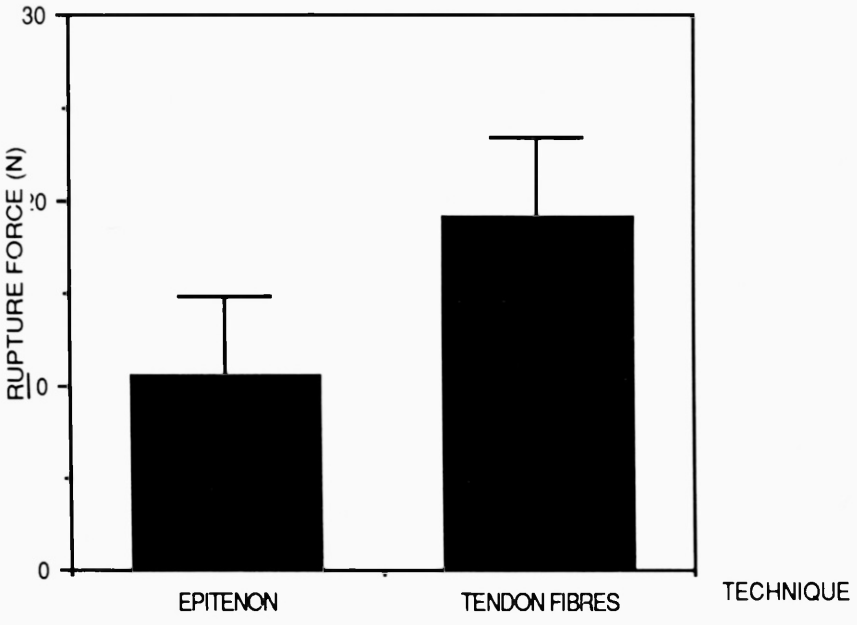


Fig 3.3: Holding strength of 6 mm transverse pass of 5-0 stainless steel suture in the epitenon and within tendon fibres . Mean $\pm$1 standard deviation , N=50

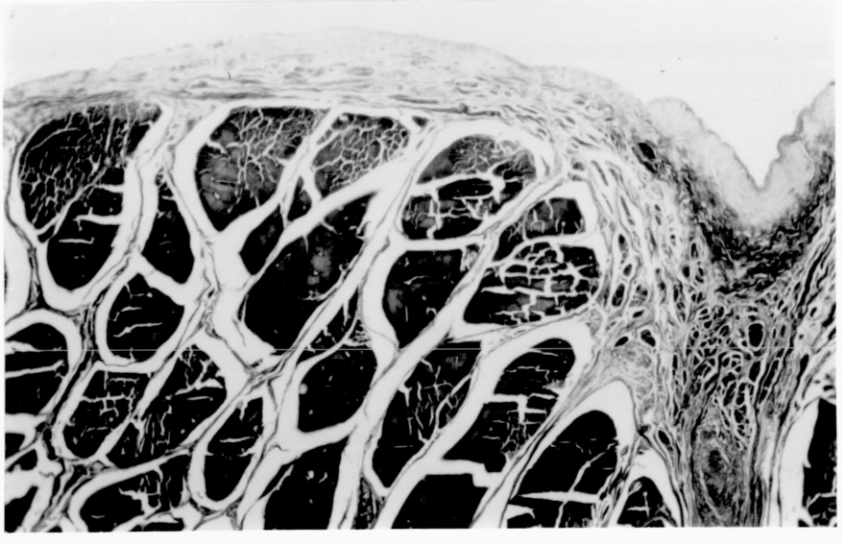


Fig 3.4: The transverse section of the palmar surface of the flexor digitorum profundus tendon at the level of the middle phalanx. The epitenon is the fragile layer of the loose connective tissue of variable thickness and tendon fibres are dense connective tissue. Stain: Azan trichrome, Mag. 300X

3.4 Effect of locking loops on the strength of suture technique and mechanism of failure of such loops

As part of the experimental study aiming to design a better suturing technique, the effect of locking loops on gap formation and ultimate strength of the repair, and mechanisms of failure of such loops, have been investigated in some detail.

3.4.1 Methods and materials

The aim of this work was to determine the relative contributions of particular features such as transverse passes and locking loops to the total strength of suture techniques. The transverse, the modified Kessler (2 locking loops in each tendon end), the Verdan (4 locking loops) and the Ketchum (6 locking loops) configurations were applied to cadaveric human digital flexor tendons (see fig 3.5). Care was taken to use tendons of approximately equal diameter. Tendons were cut into 40 mm lengths and the transverse pass of the suture was placed 10 mm from the cut end for transverse, modified Kessler, and Verdan stitches and 15 mm for Ketchum configuration, with the aid of 4x magnification. The distance between locking elements along the side of the tendon in the Verdan and Ketchum techniques was 5 mm. To ensure the maximum resistance to pull out, the suture was kept tight during insertion, with any slack in the locking loops or between them removed. Each configuration was applied to 60 separate tendons; 15 were done with each of 4/0 and 5/0 gauge multifilament stainless steel (Ethicon, UK) and monofilament polybutester (Novafil), giving a total of 240 tendons. The stainless steel suture was chosen because of its radiopaque quality, which allowed the position of the suture within the tendon to be checked radiologically while Novafil was chosen as a typical of

monofilament non absorbable polymeric sutures popular in tendon surgery. Sutured tendons were tested by distracting them on an Instron tensile testing machine at a crosshead speed of 50 mm/min. The ends of the suture were mounted in one of the grips and the end of the tendon in the other. The test was rejected if the suture failed due to the stress concentration at the edge of the clamp.

The test set-up described, consisting of one tendon end plus suture, was an approximation to one side of a tendon repair. Thus the elongation, or gap measured on the tensile test machine, approximated to a half of the gap formation to be expected in a tendon repair at any load. Two millimetres elongation was taken as representing a clinically significant change and these loads were recorded, since Ketchum, et al (1977) reported that gaps above 2 mm caused a significant deterioration in results. Thus, although the ultimate failure loads were also recorded, the forces causing gap formation are clinically more significant.

The failure mechanisms of various features were examined by x-raying as the tensile tests of stainless steel sutures proceeded, and were clearly portrayed on dental x-ray films (see fig 3.6). The dental x-ray films were held in slide mounts in the magazine of a slide projector which had had its projection lenses removed, creating a screened x-ray aperture. After each x-ray was taken the old film was replaced by remote control. This was done at 10 second intervals, giving a series of radiographs at particular loads. By adjusting the speed of the paper on the Instron chart recorder (50 mm/min) and by noting the precise timing of each x- ray exposure we were able to derive the load and gap formation value for each image. This multiple x-raying method of examination provided a good two dimensional impression of the failure of sutures inside the tendon, allowing us to see how particular features collapsed or pulled through the tendons.

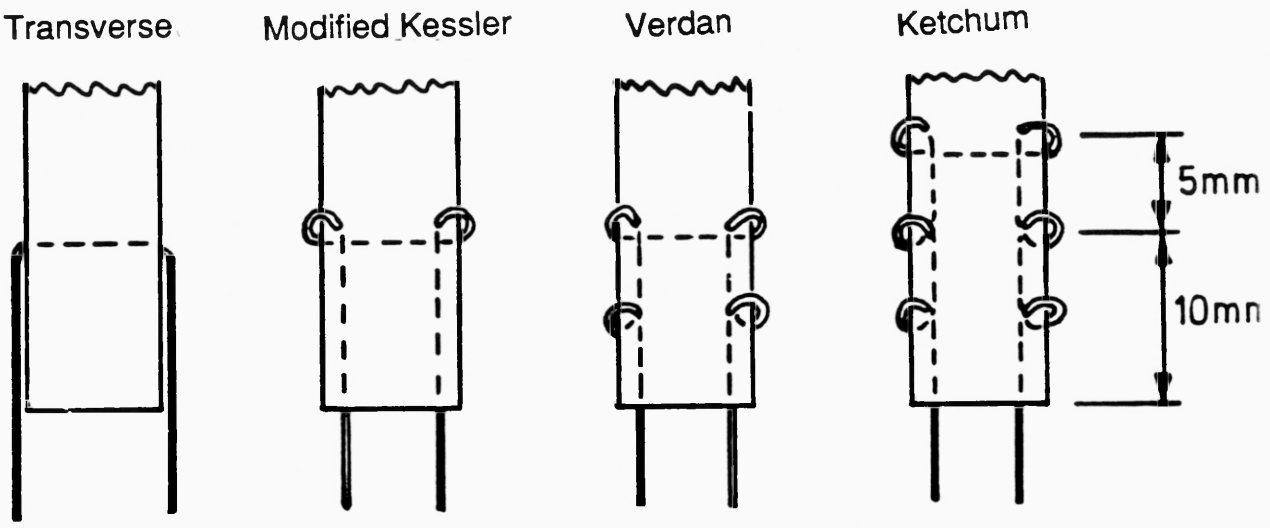


Fig 3.5:The four tendon anastomoses tested for investigating the strength of the locking loops.

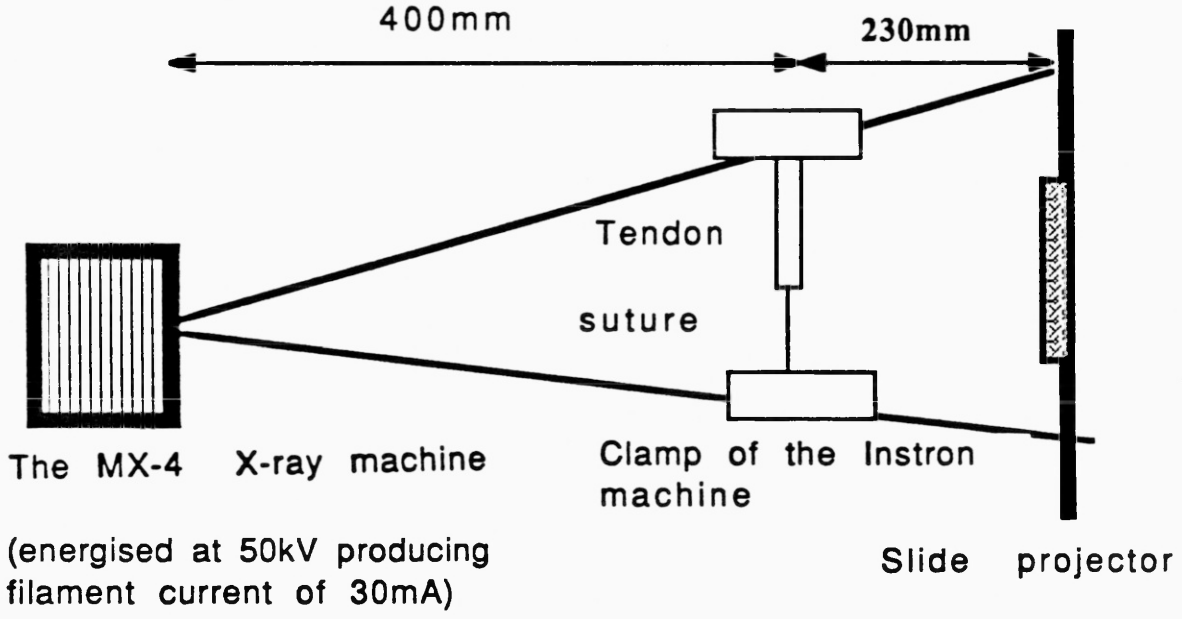


Fig 3.6: Equipment used for multiple x-raying technique

Dental x-ray film was used because it met our specific film requirements, such as contrast and high resolution. It could be inserted into a frame to be held by the slide projector. The film was developed for 5 minutes at 20 degrees Celsius and fixed in an industrial fixative for 3 minutes.

3.4.2 Results and discussion

The results from tests on various features have been examined in terms of significant gap formation and ultimate rupture. It was found that the 5/0 stainless steel suture gave no significant differences between the gap formation force and ultimate strength of the four techniques as assessed by Student's t test (see fig 3.7a). The 5/0 Novafil suture resulted in smaller gap formation and rupture producing forces than stainless steel (see fig 3.7b). These did not differ significantly with the various techniques tested. Two millimetres gap formation occurred at about 6N for stainless steel and 4 N for Novafil. The low value found for initial gap formation resulted from the absence of any peripheral stitches in this study (Wade et al, 1986).

Figure 3.8 illustrates the failure mechanism of 5/0 stainless steel sutures within the tendons with the modified Kessler, Verdan, and Ketchum techniques. It can be observed that ultimate collapse of the loops occurred at approximately 12 to 15 N with a gap formation of approximately 3 to 6 mm for all techniques.

A significant difference was noted between 4/0 and 5/0 sutures of both materials. Table 3.3 shows that a greater proportion of the 4/0 sutures pulled out of the tendon, while most 5/0 sutures snapped.

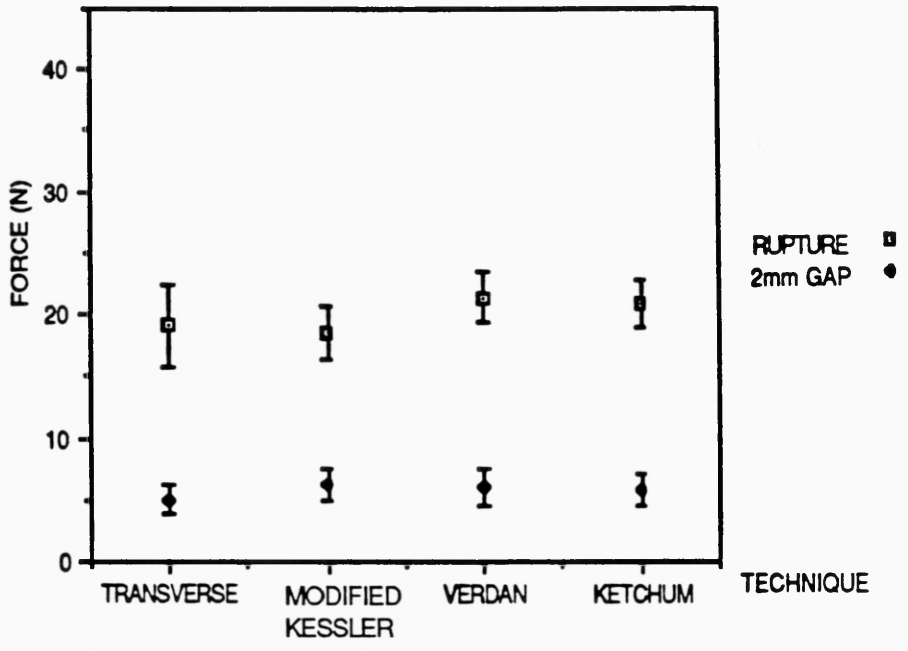


Fig 3.7a: Comparison of the strength of suture methods using 5-0 stainless steel. Mean ±1 standard deviation. N=15

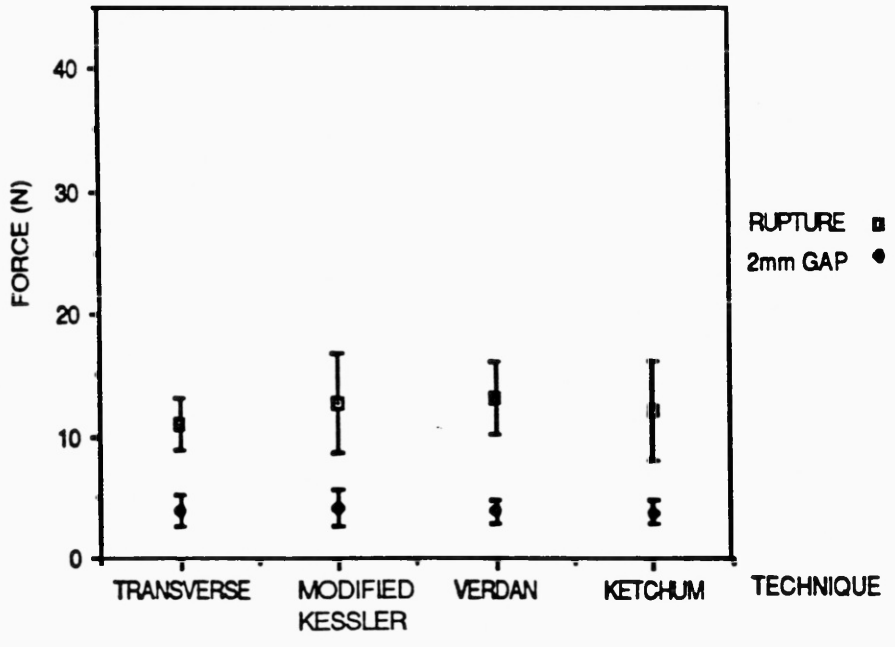
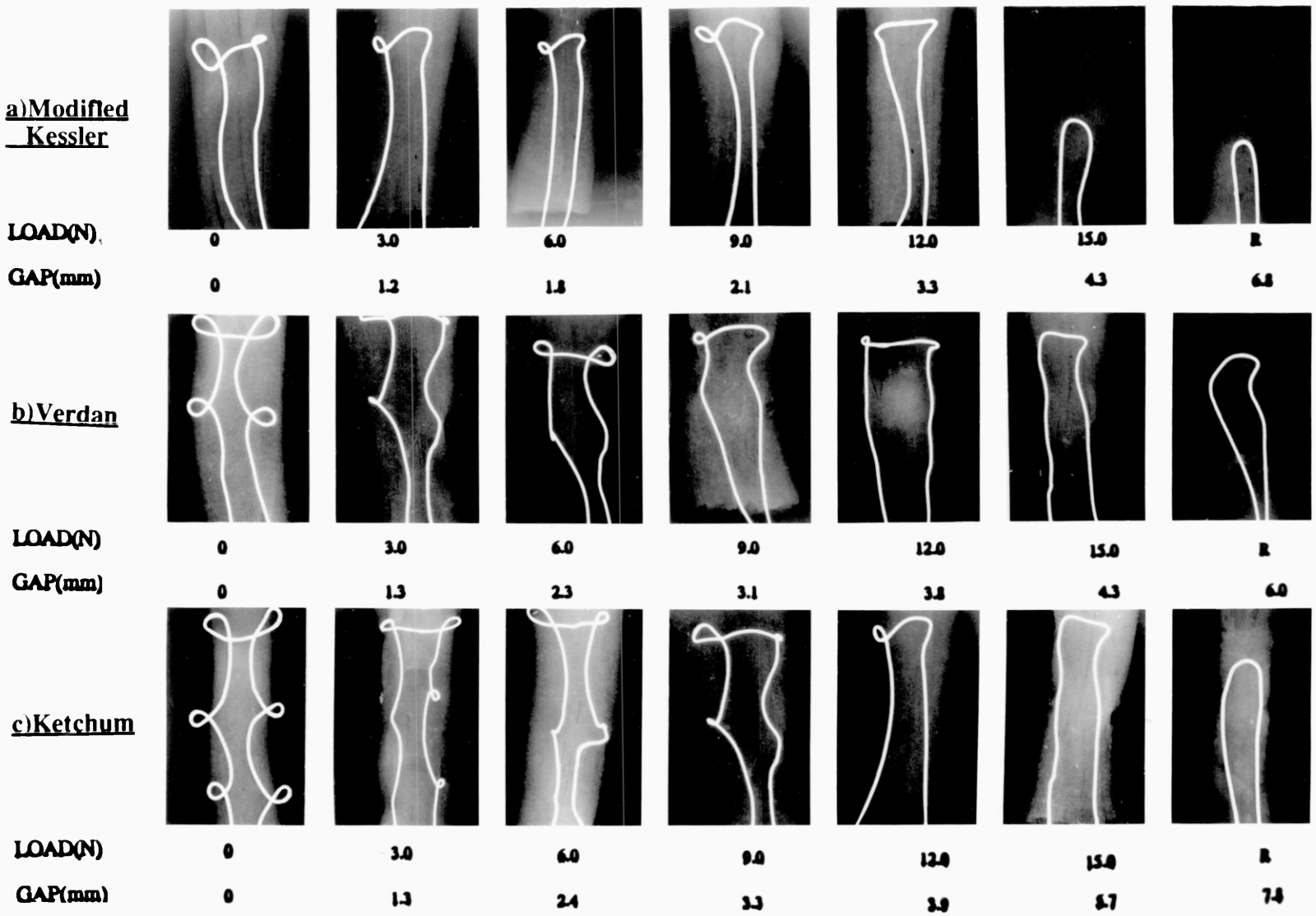


Fig 3.7b: Comparison of the strength of suture methods using 5-0 Novafil. Mean ±1 standard deviation. N=15

Fig 3.8: Failure mechanism of the locking loop techniques using 5-0 multifilament stainless steel sutures. Magnification approximately 3x. R=rupture



With 4/0 sutures, we found that the addition of locking loops added significantly to the strength of the modified Kessler technique when compared to the simple transverse stitch with both of the heavier materials ($p < 0.001$) (see fig 3.9a and 3.9b). The mean load necessary to rupture the modified Kessler stitch was 65% greater than that of the transverse stitch for 4/0 stainless steel and 40% for 4/0 Novafil. Two millimetres gap formation, however, still occurred at about 6 N for stainless steel and 5 N for Novafil.

Figure 3.10 demonstrates that complete failure of locking loops took place by 15 N in all cases. This was irrespective of the number of loops employed in the stitching technique and a gap formation of 3 to 8 mm was observed for all techniques. It is clearly seen that locking loops failed sequentially rather than by sharing the load. Each increase in the number of locking loops increased the amount of suture material liberated from the tendon end, thus increasing the size of gap formed.

The locking tendon suture was suggested as an effective method for increasing the tensile strength of repair by Kessler and Nissam in 1969. The "modified Kessler" technique of Kleinert (1981) simplified the core stitch to that tested here; this is currently the most popular clinical technique when augmented by a peripheral suture. Techniques with increased numbers of locking loops along the tendon were developed by Ketchum et al (1977) and Verdan(1979) in attempts to improve the holding strength further. Mechanical testing showed clearly that the locking loop tendon sutures do not produce a repair which is stronger than a simple transverse stitch when using 5/0 stainless steel or Novafil. The locking elements also require more operative manipulation of the tendon, which probably causes adhesions later on (Potenza, 1962).

Table 3.3: Mode of failure of monofilament polybutester (Novafil) and multifilament stainless steel

	Mode of failure of suture			
Technique	4/0 Novafil	5/0 Novafil	4/0 Stainless steel	5/0 stainless steel
	pull - break	pull - break	pull - break	pull - break
Transverse	10 5	5 10	13 2	6 9
Modified Kessler	9 6	6 9	8 7	6 9
Verdan	10 5	6 9	8 7	5 10
Ketchum	8 7	7 8	8 7	5 10

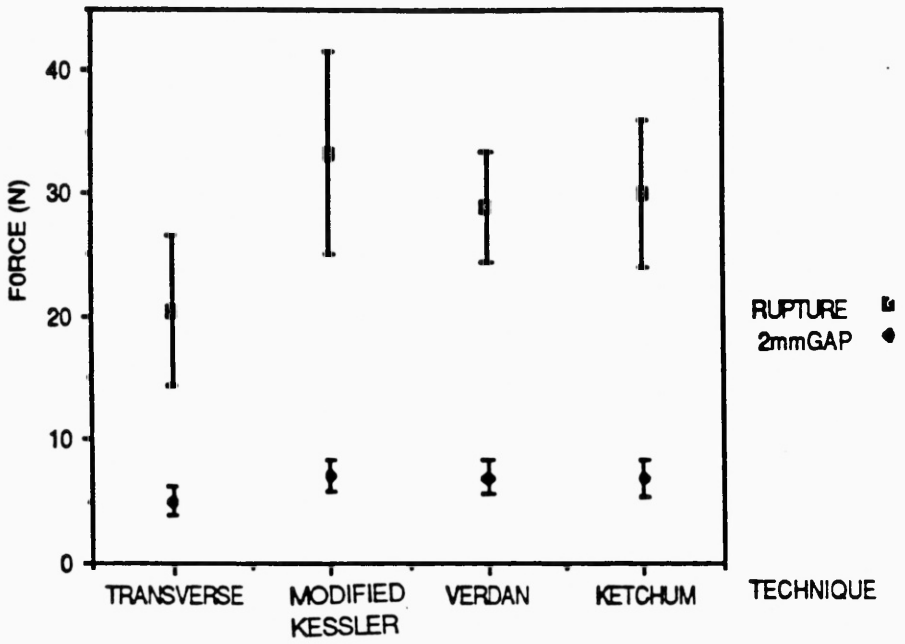


Fig 3.9a: Comparison of the strength of four suture methods using 4-0 stainless steel. Mean ±1 standard deviation. N=15

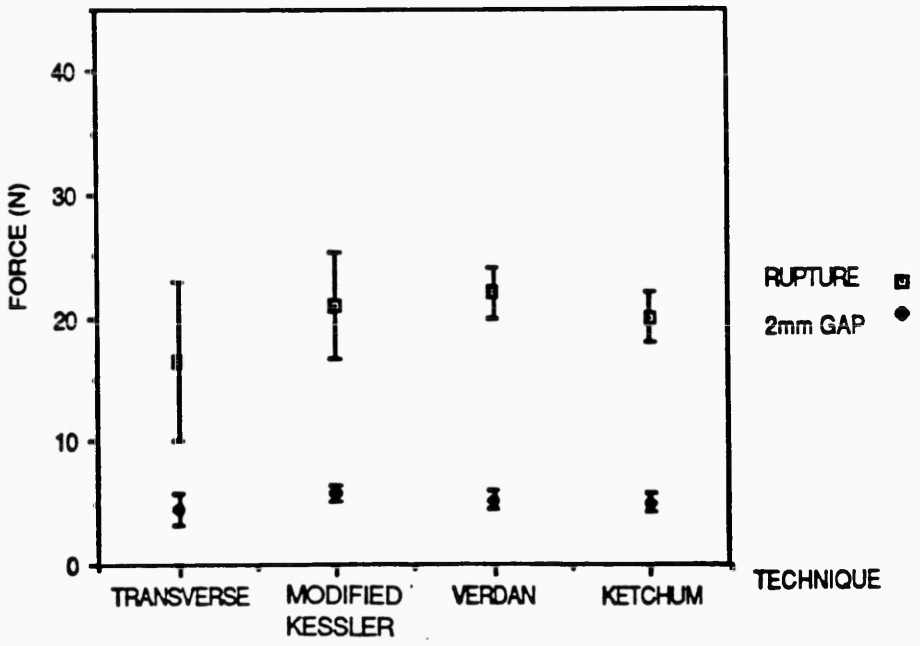
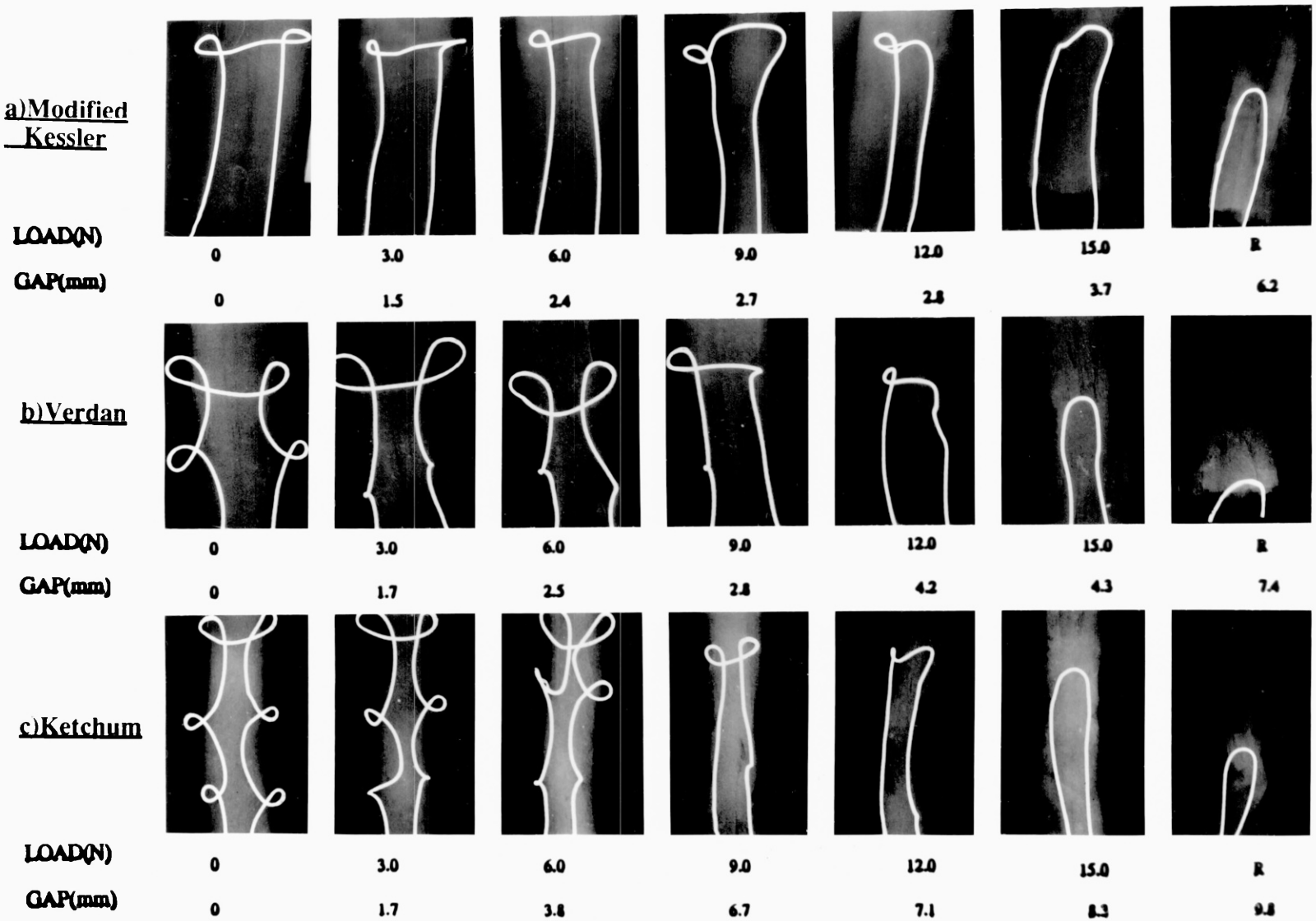


Fig 3.9b: Comparison of the strength of four suture methods using 4-0Novafil. Mean ±1 standard deviation. N=15

Fig 3.10: Failure mechanism of locking loop techniques using 4-0 multifilament stainless steel sutures. Magnification approximately 3x.
R= rupture



The modified Kessler configurations in the tendon exhibited greater pull out strength than transverse stitches when 4/0 sutures were used. This increased strength is probably associated with the larger diameter and stiffness of the suture, which results in a suture loop of larger diameter, grasping more tendon fibres and hence the larger strength. Also, the increased stiffness of the thick suture material probably made the locking loops inherently more resistant to collapsing effects. However, 4/0 sutures are rather bulky for flexor tendon repairs within the flexor tendon sheath of the finger and gap formation still occurred at low forces. Increasing the number of locking elements along the tendon still had no effect on gap formation and ultimate rupture forces, since they were loaded sequentially. Increasing the number of locking loops did, however, increase the amount of suture material liberated under load, hence increasing the size of gap formed at higher forces.

The multiple x-raying technique indicates that the locking loops along the tendon start to collapse at about 6N, resulting in large gap formation at small load. This study demonstrated that larger diameter sutures may slightly decrease the risk of failure of locking elements, but they still collapse at 15N or less. A suture technique which depends on locking loops will, therefore, often lead to gap formation at low loads and hence poor results. It was concluded that the quest for a consistently good suturing technique (i.e one which sustains a larger force before the start of gap formation at the repair site) will involve designing a stitch which does not include locking loops with the simplified form modified Kessler as the main load bearing elements.

3.5 Effect of criss cross configuration on the strength of the suture technique and mechanism of failure of criss cross

The effect of a criss cross on gap formation and ultimate strength of the repair and the mechanism of failure of such criss cross were investigated.

3.5.1 Methods and materials

In this section the aim was to determine the relative contribution of particular features such as criss cross to the total strength of suture technique. The oblique, the Bunnell, and Savage configurations (see fig 3.11) were applied to cadaveric human flexor tendons. Tendons were cut into 40 mm lengths and the transverse pass of suture was placed 10 mm for oblique and Bunnell and 20 mm for the Savage technique; the distance between two criss crosses was 5 mm for the Savage technique. Each configuration was applied to 30 tendons, 15 were done with each of 5-0 gauge stainless steel and Novafil, giving a total of 90 tendons. Sutured tendons were tested by distracting them on an Instron tensile testing machine as described in section 3.1.3.

The mechanism of failure of criss cross stitches was also examined using the multiple x-raying technique (see section 3.4.1)

3.5.2 Results and discussion

The results from various criss cross features have been examined in terms of 2 mm gap formation and ultimate rupture. It was found that the 5-0 stainless steel showed a significant difference between the three techniques with regard to mean ultimate rupture (see fig 3.12a). The results indicate that with 5-0

stainless steel the oblique stitch showed a mean ultimate strength of approximately 17 N (SD=2). This compares to 24 N (SD=3) and 30 N (SD=3) for the Bunnell and Savage configuration respectively. The 5-0 Novafil resulted in smaller rupture producing forces than stainless steel (see fig 3.12b).

However, with regard to gap formation, there was no significant difference between the oblique stitch and the Bunnell stitch when stainless steel or Novafil was applied to the tendon (see fig 3.12a, and 3.12b). With these stitches, the grasp migrates readily and pulls out of the tendon (see table 3.4). For Savage technique 2 mm gap formation occurred at 7 N (SD=1) in the case of stainless steel and at 5 N (SD=1) with Novafil. A significant difference was observed between this technique and Bunnell configuration. In more than half the tests performed the Savage configuration gripped the tendon so well that the suture snapped.

Fig 3.13 illustrates the failure mechanism of the Bunnell configuration within the tendon. It can be observed that when the Bunnell stitch was subjected to load, it converted into a single loop by longitudinal separation of tendon fibres, which eventually allow disruption of the repair. The Bunnell suture did not grasp or lock onto a bundle of fibres.

Fig 3.14 shows the Savage technique with three grasps. This technique does not collapse or pull through the tendon when subjected to the load. This is the advantage of this technique over the other methods. However, it seems to be very difficult to insert this technique, because the locking stitches mean that the length must be adjusted at each pass across the repair. Therefore, an ideal grasp for suturing technique has yet to be found and should have the following properties:

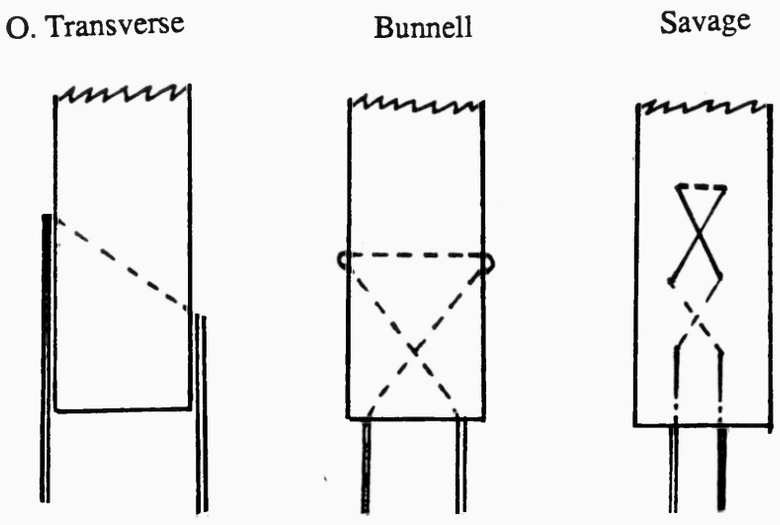


Fig 3.11: The three tendon anastomoses tested for investigating the strength of criss cross techniques

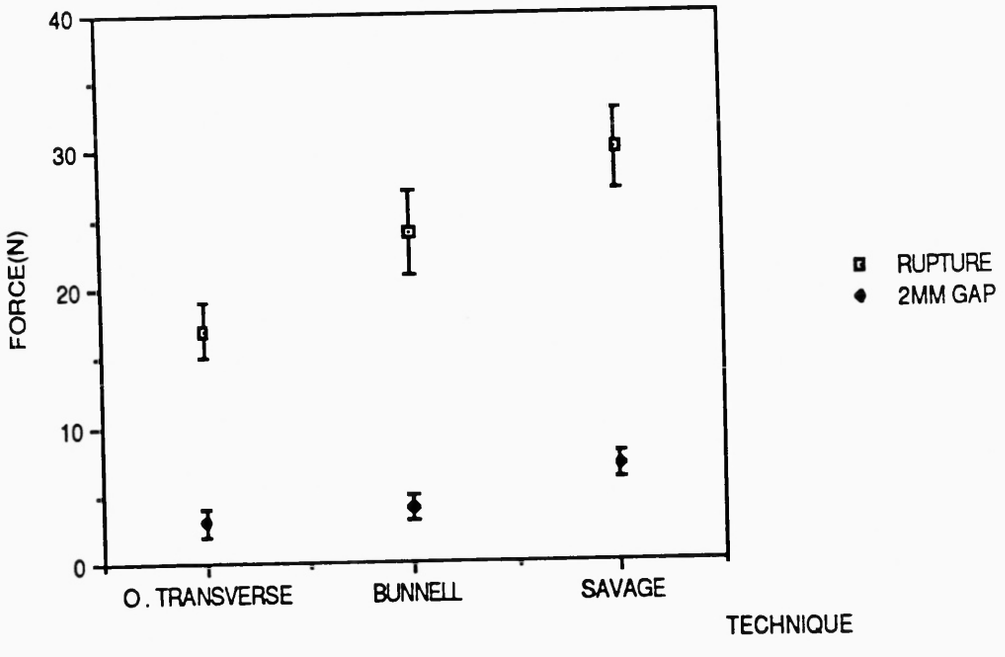


Fig 3.12a: Comparison of the strength of the three methods using 5-0 stainless steel

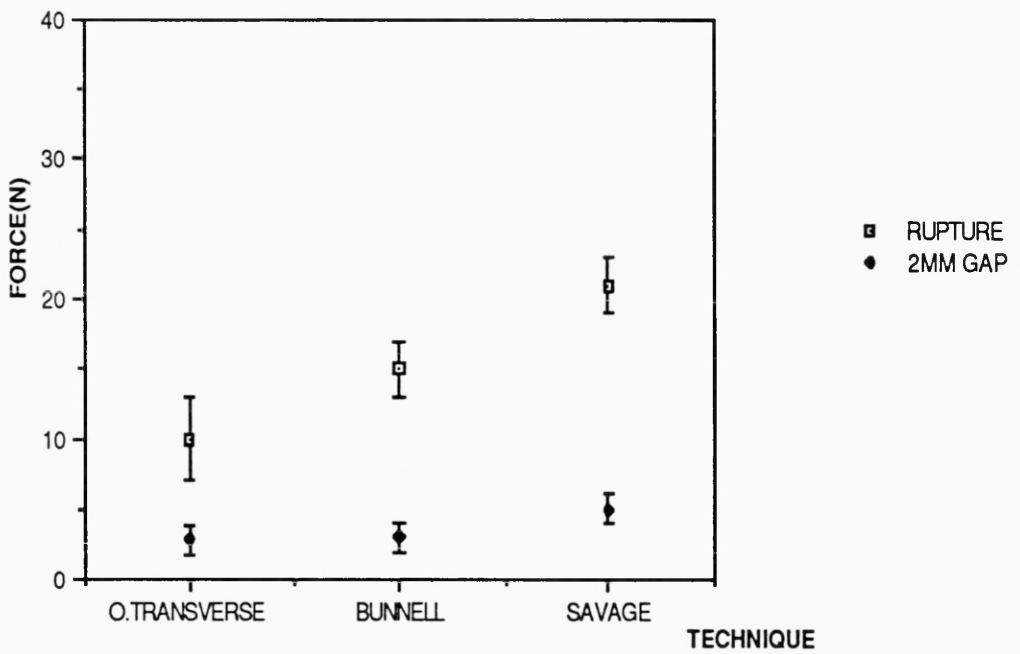
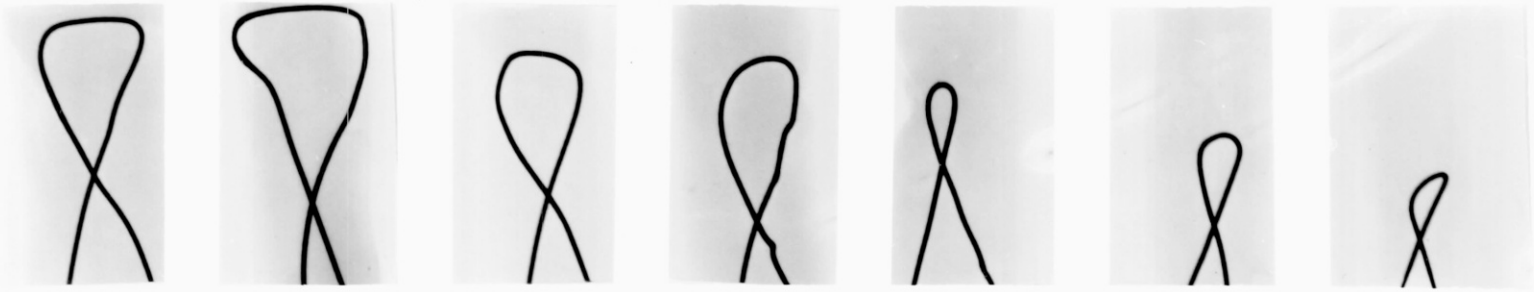


Fig 3.12b: Comparison of the strength of the three methods using 5-0 Novafil

Table 3.4: Mode of failure of 5-0 Novafil and stainless steel

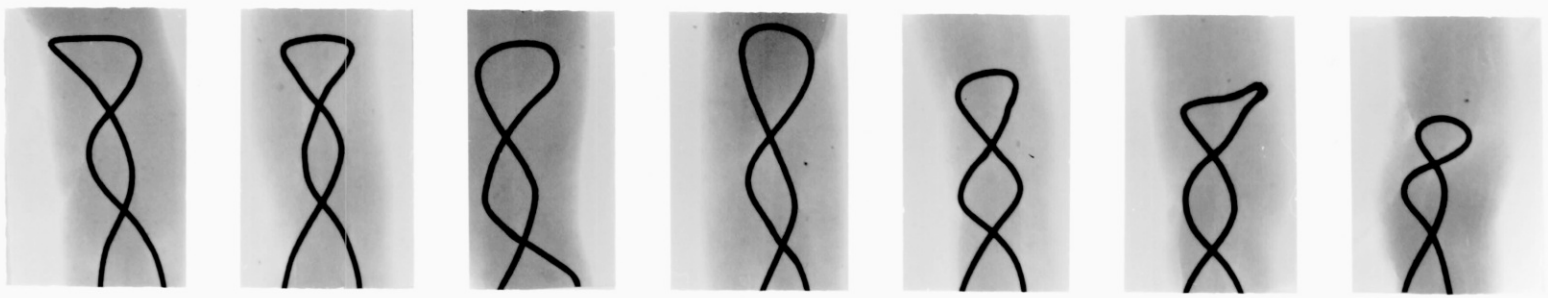
	Mode of failure of suture			
Technique	4/0 Novafil		5/0 stainless steel	
	pull	break	pull	break
Obliquely Transverse	12	3	11	4
Bunnell	9	6	10	5
Savage	3	12	4	11

FIG 3.13: MECHANISM OF FAILURE OF BUNNELL CRISS CROSS TECHNIQUE USING 5/0 STAINLESS STEEL



LOAD(N)	0	3.0	6.0	9.0	12.0	15.0	R
GAP(mm)	0	2.0	2.5	3.0	4.0	5.3	6.9

FIG 3.14: MECHANISM OF FAILURE OF SAVAGE TECHNIQUE USING 5/0 STAINLESS STEEL



LOAD(N)	0	3.0	6.0	9.0	12.0	15.0	R
GAP(mm)	0	1.2	1.8	2.1	2.3	2.5	3.0

1) It must not be difficult to insert.

2) It must have a good grasp that does not lock the stitch or pull through the tendon.

3) It must be very strong.

4) It must cause no interference with blood supply.

5) Stitches must be placed in the tendon fibres and not within the epitenon.

6) It should not include locking loops as the main load bearing features.

7) It should not include criss cross as the main load bearing features.

3.6 Design of new peripheral and core stitches

The mechanical factors which influence the holding power of the tendon repair have been studied in previous sections. The aim of this section was to use this information to design a new peripheral and core stitch of tendon repair. The ultimate strength and gap formation of the repair would be compared to the well known techniques.

3.6.1 Methods and materials

90 cadaveric human finger flexor tendons were obtained (see section 3.1.3) and divided into 6 groups of 15 tendons. 5-0 Novafil was used for the peripheral and core stitches.

In group I a new core stitch was applied to the tendon. Details of insertion of this stitch are shown in fig 3.15. The suture was inserted as illustrated, with the transverse stitch component passing approximately 15 mm from the cut end. This process was repeated in the other tendon with the same needle. The tendon ends were then approximated and a knot was tied between the tendon ends.

In group II, a new peripheral stitch was applied. Figure 3.16 shows the plan of the peripheral stitches. It comprised four grasps and eight suture strands. Stitches parallel to the direction of the fibres were inserted in the epitenon layer 5 mm from each cut end. These stitches were, in turn, locked by transverse stitches which are placed within the tendon fibres. The stitching was terminated by a final knot on the surface of the tendon. The knot could be drawn to set a desired degree of contact. In this technique the suture only grasped the periphery of the tendon. It was therefore in the area which is

believed to be nourished by diffusion from synovial fluid and away from central vascularized area.

In group III, the new core and peripheral stitch were used together.

The repairs were then tested using an Instron tensile testing machine as before (see section 3.1.3), the ends of the tendon being clamped well beyond the limits of the repair. The load was recorded when a 2 mm gap formed between the tendon ends and ultimate rupture occurred.

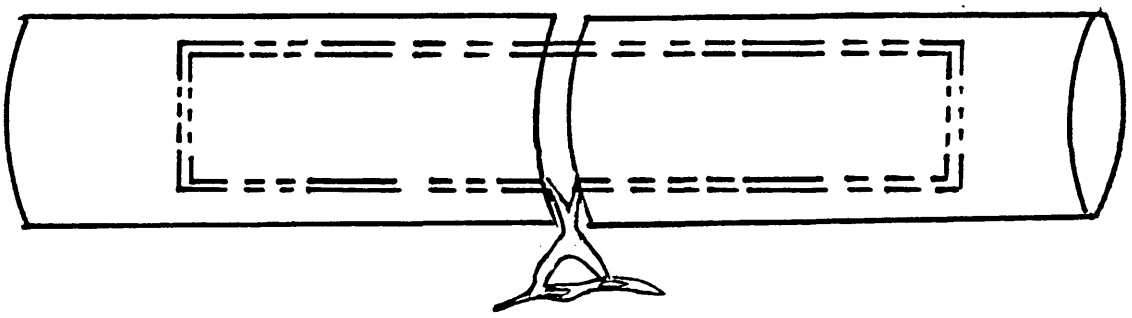


Fig 3.15: The configuration of the new core stitch

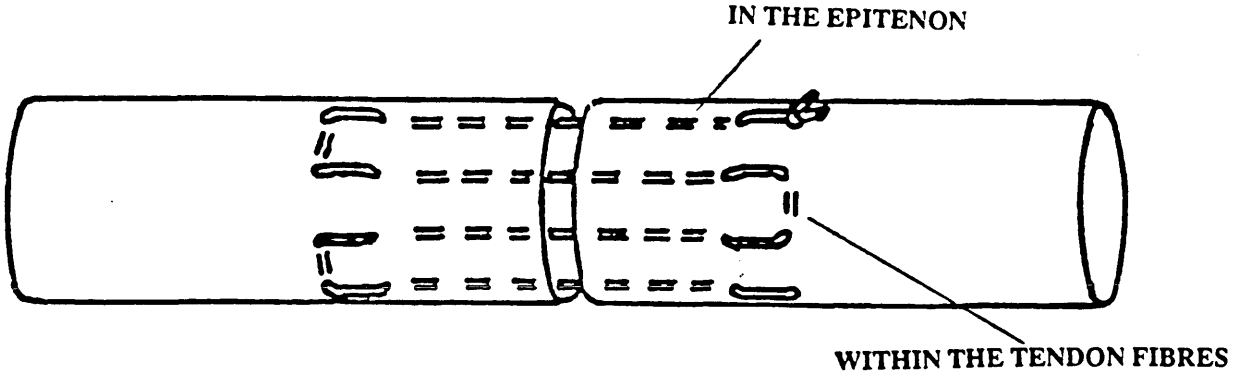


Fig 3.16: Configuration of the new peripheral stitch

3.6.2 Results and discussion

The strengthsof the new peripheral, core and complete techniques are shown in fig 3.17. The new modification was found to increase the force at which a 2 mm gap formed by 230% and the maximum strength of the repair by 77.8 % when compared to the widely used modified Kessler technique.

The new peripheral stitch was found to increase the rupture strength by 150% and the load at which a 2 mm gap formed by 100%, when compared with the over and over stitch. Comparison of the new peripheral stitch with the continuous Halsted suture found it to be significantly more resistant to 2 mm gap formation ($p < 0.03$) and rupture producing forces ($p < 0.001$).

The new technique was chosen for the tendon repair for the following reasons:

1)The new technique, by achieving anchorage wholly within the tendon fibres, has greater strength with regard to 2 mm gap and ultimate rupture.

2) Multiple passes, particularly in a running configuration, share the load and hence multiply the strength of the suture material used. This peripheral stitch alone is as strong as the widely used Kleinert modification of the Kessler core (1981) with an over and over circumferential stitch (Wade et al., 1986).

3) The technique also minimises suture material on the surface of the tendon, which should reduce foreign body reaction where adhesion formation is known to occur (Matthews and Richards, 1976).

4) The point at which suture material grasps the surface is 5 mm away from the cut ends. This is important because there is thought to be some softening in

the tendon adjacent to the cut ends following the injury (Mason and Allen, 1941).

5) The technique presents a smooth junction, which is not thicker than the normal tendon, thereby allowing easy gliding within the sheath. Eversion of the edges of the cut tendon ends is avoided by passing the suture through the epitenon close to the ends (see fig 3.16).

The important difference between the new peripheral suturing method presented here and the range of pre-existing methods tested for comparison is that it is the only one in which the transverse passes across the tendon fibre direction are into the tendon fibres. The traditional horizontal mattress and Halsted methods take the opposite path, but were originally designed for wound closure and intestinal anastomoses (Nealon, 1979), rather than tendon repair. It has been shown recently (Wade et al., 1989) that the Halsted peripheral suture was significantly stronger than the commonly used "over and over" stitch, but that work was done before it was known that stitches are held more securely within the tendon fibres rather than the epitenon.

Since the holding power of the tendon fibres with this technique is stronger than the sutures, which always snap rather than pulling out, the only remaining possibility for increasing the repair strength is to have more passes of suture and/or stronger suture material.

Since also, the deep transverse passes are easily inserted and still allow the running configuration to draw the tendon ends together, we feel that there is no reason to use complex locking features such as those described by Savage (1985).

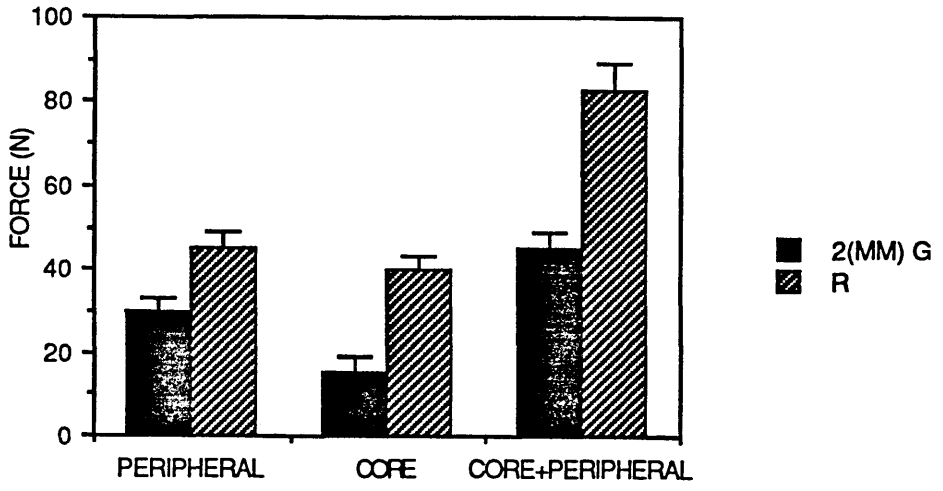


Fig 3.17: Strength of the new peripheral, core, and peripheral and core stitches together with regard to rupture and 2 mm gap formation. Mean ±1 Standard deviation. N=15

Chapter 4: Factors influencing softening and adhesions (in vivo studies)

4.0 Introduction

Peritendinous adhesions which develop around the flexor tendon after operation or injury are still a major problem in surgery of the hand. The adhesions that were once believed to be part of the healing process cause an almost inevitable functional disability during the biological response of the tissue to the injury (see chapter 1). To achieve better gliding function of flexor tendons, continuous efforts are being made to reduce adhesion without adversely affecting the healing process itself. A variety of techniques have been used, such as the introduction of a mechanical barrier between the tendon and proliferating tissue (Ashley and Wilson, 1964; Boyes, 1970; Potenza, 1965), tenolysis (Fetrow, 1967; James, 1969), early mobilisation (Gelbermann and Menon, 1980; Strickland and Gloogovac, 1980; Lister et al., 1977; Duran, 1975), preventing gap formation (Seradge, 1983; Ketchum et al., 1977), reducing trauma to the tendon (Bunnell, 1918; Potenza; 1963) and tendon sheath (Lister, 1983).

Although it has been shown that the above factors may partly reduce or eliminate adhesions, there are many factors yet to be investigated which may also influence adhesion formation. This thesis examines the effect of absorbable and non absorbable suture materials and the blood supply of vinculae on adhesion formation.

Softening, which is revealed at an early stage of tendon repair, creates another problem in the surgery of the hand. During the first two weeks after suturing, the tensile strength of the sutured tendon decreases to considerably less than

that found to be present immediately following an operation (Mason and Allen, 1941). During these few days the ends become soft and are held together by a gelatinous exudate, which possesses the minimum of tensile strength. These softened stumps have considerably less holding power for the sutures than was present when they were introduced, and when stress is applied to the sutures, instead of breaking, they simply pull out. The mechanism causing this phenomenon is not yet understood. It is the purpose of this study to investigate the influence of the following factors:

1) Vincular blood supply
2) Deleterious tissue reaction to suture material:
 a) absorbable
 b) non absorbable
3) inflammatory changes within tendon as part of healing process

This was essentially a mechanical study although specimens were used for histology for correlation with the mechanical findings.

4.1 Methods and materials

4.1.1 Experimental subjects

The chicken was chosen as the experimental subject. The chicken foot has a readily available digital mechanism which is remarkably similar to the human hand. The tendon sheath, tendon structures, blood supply are all similar to human. The chief point of differences is that the flexor digitorum superficialis does not wrap around the flexor digitorum profundus tendon dorsally after the former bifurcates, but inserts directly into the base of the second phalanx on each side of the fibrocartilagenous plate. There are complex reflections of filmy mesotenon between the tendon sheath and the flexor digitorum superficialis from its region of bifurcation to its insertion supplying blood to the flexor digitorum superficialis. The flexor digitorum profundus is smaller and somewhat firmer than that of the adult human. It has one vinculum longum and one vinculum brevis, similar in all respects to the human (see also chapter 2).

Chicken blood has nucleated red blood cells and a predominance of lymphocytes, which must be recognised, but does not invalidate microscopic interpretation.

The tissue healing process of the chicken and the human could be usefully compared and the chicken digit was an excellent medium to study tendon healing from functional, macroscopic and microscopic points of view in a controlled manner.

4.1.2 Caging and feeding

Chickens were kept in pens of floor area of 120 cms by 180 cms and a height of 240 cms. They were white Leghorn adult cockerels, weight 1.8 to 2.5

kilograms, ages 3-4 month on arrival. The temperature in the room was 21 degrees centigrade with relative humidity of 50- 60%. The pens were cleaned out completely once a day with sawdust being removed, the floor of the pen being cleaned, disinfected and new sawdust replaced.
The chickens were fed a standard chopped diet with added grain and shell.

4.1.3 Design of operative group

A minimum of six chickens per group was advised. Four were used for tensile testing and two for histology. The experimental groups chosen to give information on the problem discussed in the introduction and chapter 1 were:

1) The effect of absorbable suture material on softening and adhesions
2) The effect of non-absorbable suture material on softening and adhesions
3) The effect of vincular blood supply on adhesion and softening
4)The effect of inflammatory changes within tendon as part of healing process on softening

Absorbable suture material

The aim of this experiment was to examine the extent of adhesion formation and the tendon softening developing in the presence of early mobilisation and absorbable Polytrimethylene carbonate (Maxon) suture material.

The right leg was operated in the area shown in fig 4.1a. It is important to determine the exact location of the operation in order to know whether the site of operation is in the vascular or avascular zones (see chapter 3). Polytrimethylene carbonate suture (5-0) was embedded longitudinally for one centimetre within the flexor digitorum profundus tendon, always using an identical type of fine needle. The suture was anchored, with an external knot

at both ends for stabilisation.

Non absorbable suture material

The same procedure was carried out as above, except the suture material in this case was 5-0 polybutester (Novafil).

Vincular blood supply

The aim of this experiment was to investigate whether adhesions or softening occurred with cutting vinculae, with early mobilisation, while the tendon is intact.

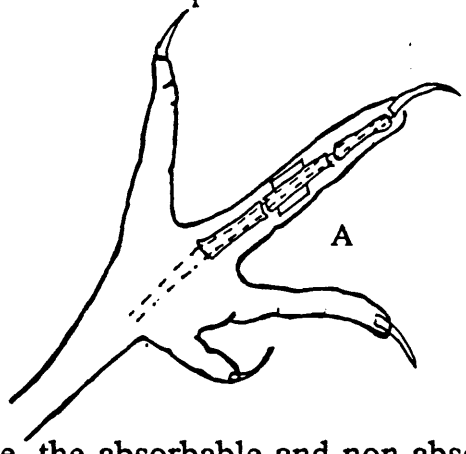
The sheath was opened longitudinally through a one centimetre incision at the levels of the first and third phalanx (see fig 4.1b). The flexor digitorum profundus was exposed and vinculum longus and brevis isolated and sharply severed with scissors .

Inflammatory changes within tendon

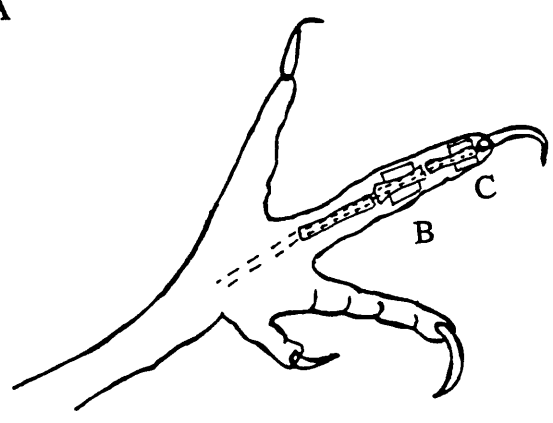
The aim of this experiment was to examine whether the softening is due to inflammatory changes within the tendon.

The sheath was opened through a 0.5 cm incision at the level of the third phalanx (see fig 4.1c). The profundus tendon was isolated and sharply severed with a number 15 blade at this level. The loss of tension and motion are very important effects here.

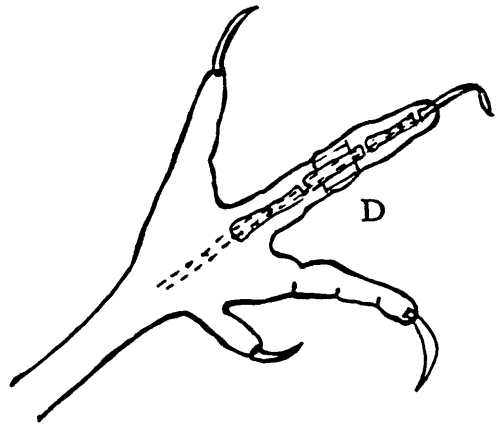
Fig 4.1: Diagram of the site of operation



a) in the middle toe, the absorbable and non absorbable suture material was placed at site A



b) Site B and C were where the vinculae were removed and tendon remained intact.



c) Site D received a cut

The time chosen for the sacrifice of animals was at 5, 15, and 45 days. The critical period for softening and adhesion is during this period.

132 chickens were used in this series of experiments. Twenty four were used for histology and were not included in mechanical testing. The remaining were divided equally into each group with 4 chickens at each time interval.

4.1.4 Pre-operative preparation

The chicken was starved for twelve to fifteen hours pre-operatively and during this period the feet were scrubbed with soap and water and manicured.

Anaesthesia was induced by inhalation. The substances used were;
oxygen 21 / min
Nitrous oxide 11/ min
Halothane 0.5-1.5%

This was administered through a loose fitting rubber mask over the chicken's head. The anaesthetic machine used was a Penlon. The Halothane was reduced where possible during less stimulating points of the operation. It was found that only the skin incision and skin closure required the full 1.5% of Halothane.

The wings and trunk were wrapped with a towel to prevent excessive movement, and the chicken was positioned chest down. The bird was placed with its feet plantar side up on a small plastic box. Its feet were strapped to this box with water proof tape (sleek) so that the digits were kept straight. The feet were again thoroughly cleaned with Hibitane (chlorohexidine in spirit). No tourniquet was applied and formal draping was carried out.
In all the cases the right leg was operated on and the left leg was left intact as a

control. This was carried out because there is a difference between one foot and two feet surgery. When only one foot is subjected to surgery, the action of the normal foot is able to protect the foot which has been operated on. This is equivalent to "guarded movement " in human. When both feet are subjected to surgery, no such "guarded movement " is possible.

4.1.5 Operative technique

All the operations were carried out in a similar way, but each group had a slightly different procedure for the tendon itself, as detailed in section 4.1.3.

The operation was performed under clean but non- sterile conditions. Surgery on chickens was carried out using 4x magnification loupes and the following instruments:

1) Thackray microsurgery needle holder
2) Two pairs of Jeweller's forceps
3) Microsurgical scissors
4) Suture material
5) Scalpel

Incision was made on the volar surface of the middle digit of the foot. Care was taken to spare the neurovascular bundles and the large geniculate vessels. The flexor sheath was exposed and incised longitudinally. The deep flexor tendon was displaced from the below the superficialis tendons and supported with a pair of non toothed forceps. The appropriate operation was performed as described in section 4.1.3. The tendons were then replaced in their correct position and the sheath was simply excised. The closure of the flexor sheath in chickens after primary tendon repair does not improve either tendon nutrition or tendon gliding (Manske, 1984). He demonstrated that the tendon sheath which had been closed at the time of the tendon repair had lost its synovial

characteristics after 3 weeks and by 6 weeks a new synovial lining could be identified and also that closure of the sheath may narrow the fibro- osseous tunnel, making it more difficult for the tendon to glide. Skin closure was with interrupted 4-0 Polybutester suture. Gauze was placed over each incision and "sleek" waterproof tape was placed over the digit. No splintage was used so that that chicken could move freely in the cage.

Immediately after operation the chicken was laid in a box in a corner of the operating room while it recovered from the anaesthetic. An early practice of returning the bird to its cage directly after operation and while still drowsy was abandoned because some of these birds were pecked by their more alert companions in the pen. Keeping them half an hour in the operating room prevented this. The birds were then returned to the pen and were fed a finer chop.

4.1.6 Post mortem method

The animals were sacrificed under general anaesthesia by an intravenous injection of 5 ml Euthatal (sodium thiopentone) into a vein. The legs were removed and the chicken later incinerated. For mechanical testing legs were put in plastic bags, marked with a waterproof pen and deep frozen until testing. For histological specimens the middle digit was first stripped of skin and then disarticulated at the metacarpal phalangeal joint and preserved in 10% formalin.

4.1.7 Histology

The tendons of the third toe of the chicken were examined histologically. Each specimen was prepared in a standard manner. Excess formalin was removed by means of running tap water. The specimen was then processed through a

series of alcohol solutions of increasing concentration up to absolute alcohol. It was finally immersed in a clearing agent (Histo clear, Data Diagnostic Ltd.) for 16 to 20 hours.

Infiltration with paraffin wax was begun by transferring the specimen into molten paraffin wax (paraplast plus with DM50) that was maintained at a temperature of 58 to 60 degrees centigrade. Four changes of wax were made during the following eight hours. The excess liquid was then poured away and the specimen was left to cool overnight.

On the following day, the specimen was embedded in a vacuum chamber using two changes of wax over a twelve hour period. Finally the specimen was carefully embedded in fresh wax in brass moulds. The paraffin block in which the specimen had been embedded was then cooled rapidly in water and stored in a refrigerator prior to microtomy.

Sections were cut on a Lietze "Mionot" rotary microtome with a feather disposable blade system. The specimen was orientated so that the claw was cut last in the traverse of the knife. Those specimens whose centre had been inadequately infiltrated with wax were returned to the vacuum chamber for a further six hours. This procedure was repeated if necessary. When the medial surface of the specimen had been evenly faced off, serial histology sections of 5 micron thickness were taken. Twelve representative sections which clearly demonstrated the tendon, sheath, vinculae, and suture were kept for staining.Twelve representative sections from the middle zone of the specimen were stained with Haematoxylin and eosin.

Much of the development work for the above processing was done in collaboration with Experimental Pathology Service, who subsequently did all histology processing on a commercial basis.

4.1.8 Biomechanical analysis

The third toe was prepared for biomechanical examination as follows:
The legs were unfrozen by immersing them, still in plastic bag, in water. The maximum time between unfreezing and finishing testing was two hours. After thawing, the legs were pinned on a board, an incision was made through the skin along the flexor surface from the ankle to the metatarsal pad and the tendon of flexor profundus was isolated. Amputation of the metatarsophalangeal joint was then carried out and all the other tendons (i.e. perforatus and perforatus et perforans) were cut at that level (see fig 4.2). This was the proximal extremity of the biomechanical model. The flexor profundus tendon was divided distally over the distal interphalangeal joint, just proximal to its insertion but distal to vinculum brevis. This procedure meant that the tendon was only connected to the sheath by any remaining vinculae and any adhesions that had formed. In this experiment the vinculae were left intact in both legs and it was assumed that in a comparison between left and right legs the effect of vinculae could be cancelled out and that any difference would be due to adhesion formation between the operated tendon and the sheath. It was possible to surgically divide the vinculae before tensile testing so that only adhesions and or swelling of the tendon would provide resistance. However, the technical difficulty, surgical trauma and uncertainty of doing this would probably introduce more error than it removes. One could neither be certain that all the vinculae would be cut nor that the adhesions would be undamaged. The vinculae were therefore left intact.

The distal phalanx was then clamped into the lower jaw (i.e. static part) of a tensile test machine and the proximal free end of the tendon to the moving upper jaw of the machine (Instron material testing machine, Model 1122).

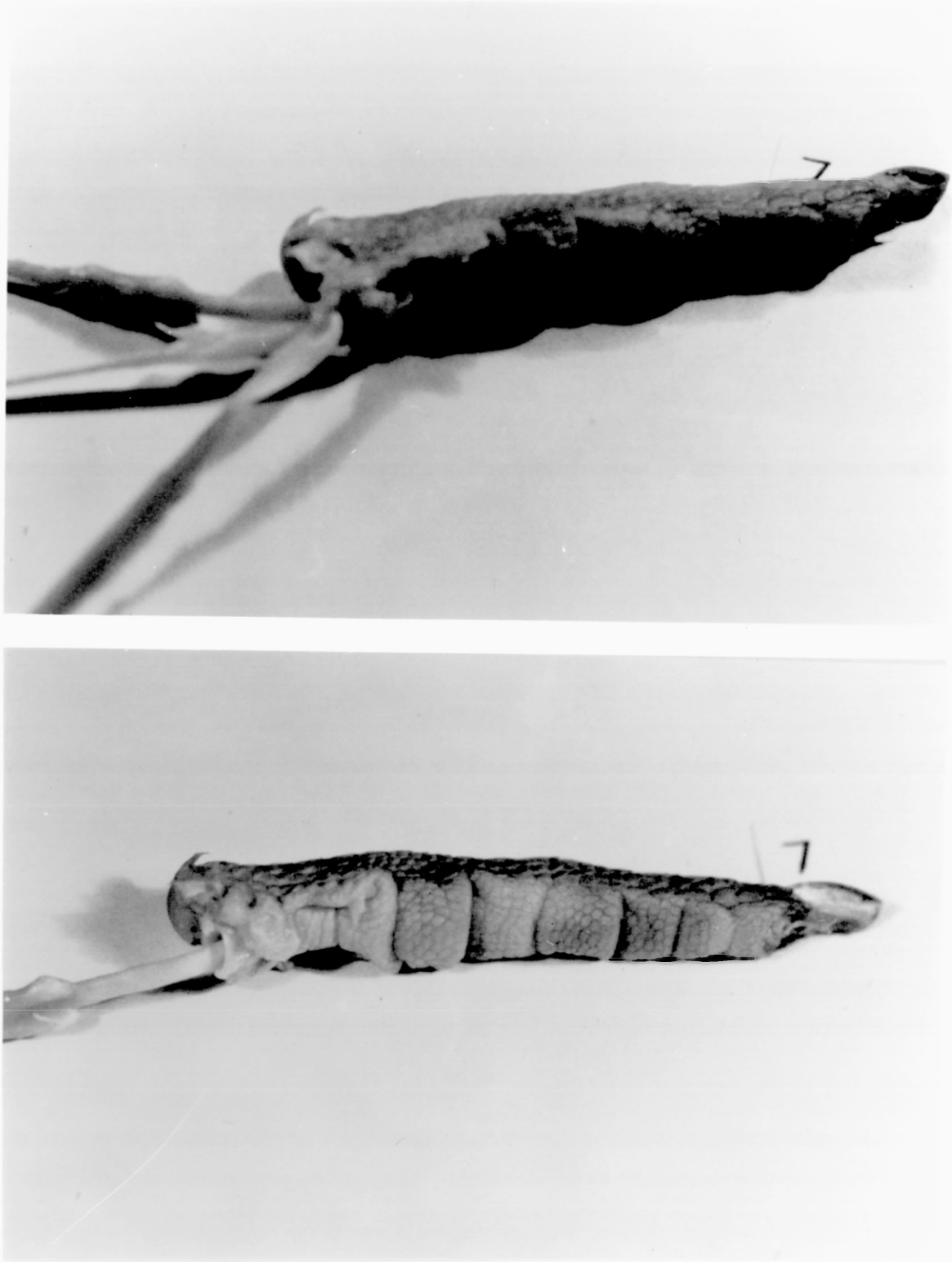


Fig 4.2: Preparation of the chicken foot for adhesion testing.

4.1.9 Adhesion testing

The samples were tested in tension at a crosshead speed of 20 mm /min. Tests were carried out in the air at room temperature . Maximum deflection used was 100N and chart drive was at a ratio of 5:1 proportional to the crosshead speed movement. A typical tracing showed the maximum force needed to pull the tendon from its sheath, the peaks where the vinculae snapped, and the end point where the tendon came out of its sheath (see fig 4.3). Measurement of the area under the curve gives the work done in removing the tendon in milli Joules. This energy was a measurement of the work required to overcome friction, to rupture the vinculae, and to overcome adhesions. The adhesion test was carried out at 5, 15 and 45 days.

4.1.10 Softening test

Softening of a divided tendon has been considered to occur near the cut ends as part of the healing process. Such a change has obvious significance for the holding power of tendon for inserted stitches and a series of measurements were made to demonstrate and quantify softening.

After the adhesion tests the profundus tendon of the third toe which had been removed from its sheath was placed on a board, kept moist and divided into segments for softening tests. The cuts were at the suture line and at 18 mm above proximal and distal to this part (see fig 4.4).

In groups I and II, testing was carried out by passing a 5-0 multifilament stainless steel wire on a 25 mm cutting needle through the tendon 3 mm from each cut surface, that is, 3 mm from the suture site both proximally and distally and at 15 mm from the suture site, both proximally and distally. In group III the wire was placed within the tendon with the gaps of 3 mm each up

to 15 mm above the vinculum longum. In group IV the wire was inserted 3 mm and 15 mm from cut end both proximally and distally. These procedures in all groups were carried out on both the control and operated foot.

The tendon segment was then clamped in the upper jaw of the Instron and both ends of the wire in the lower jaw. The machine was then started and the maximum work done in causing the wire to cut out through the end of the tendon was recorded on graph paper. The softening tests were carried out at 5 and 15 days.

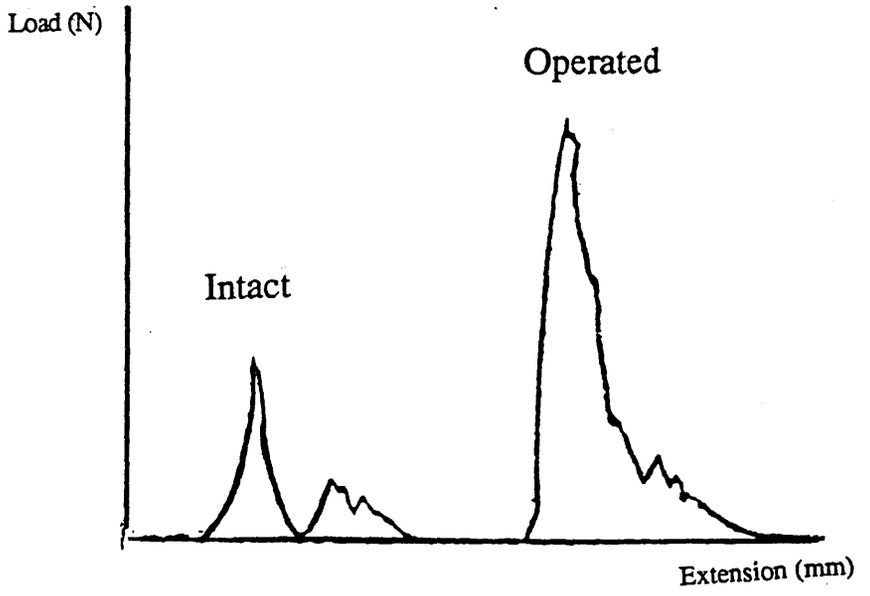


Fig 4.3: A typical tracing showed the maximum force need to pull the tendon from its sheath and the end point where the tendon come out.

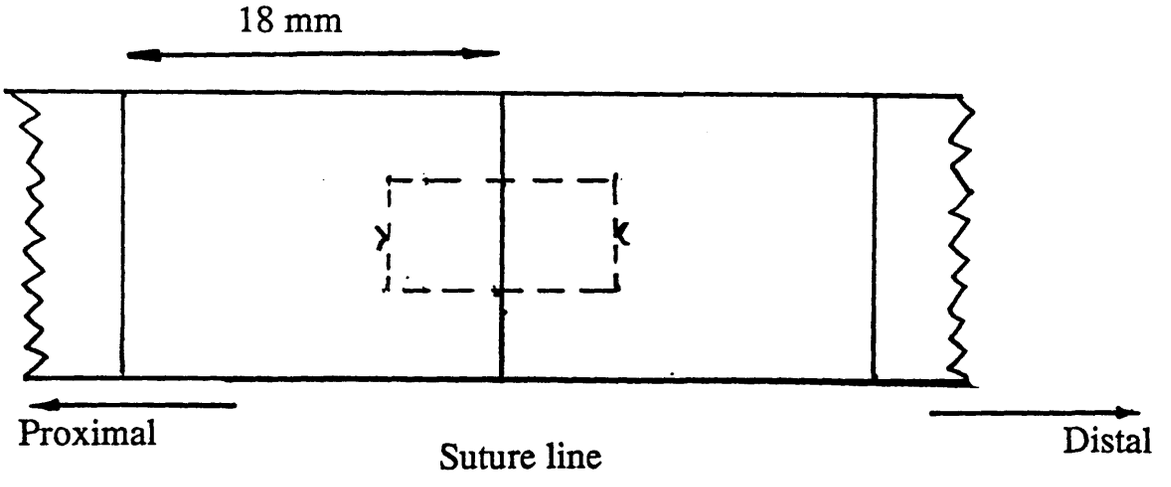


Fig 4.4: The cuts at the suture line and at 18 mm below the proximal and distal part.

4.2 Results and discussion

4.2.1 Adhesion test

Suture reactivity : non-absorbable suture material (polybutester)

The energy per kilogram body weight required to pull out the profundus tendon from the third toe, when polybutester suture was applied to the tendon is shown in table 4.1. The results were analysed using Student's paired "t" test. There was no significant difference between operated and control foot at 5, 15 and 45 days.

Suture reactivity: absorbable suture material (polytrimethylene carbonate)

The energy per kilogram body weight required to pull out the profundus tendon from the third toe, when absorbable suture was applied to the tendon, is shown in table 4.2. No significant difference was observed between operated and control feet at 5, 15 and 45 days.

This study suggests that the presence of suture material alone is not a contributory factor to adhesion. Matthews and Richards (1967) showed that this is only so if it is accompanied by sheath excision and immobilisation, as well as sutured tendon.

Table 4.1: Energy (milli Joules) required to pull out tendons from the sheath(non absorbable polybutester suture) Mean ±SD, N=4

Time (days)	Control tendon		Operated tendon
5	168.5±40	P< 0.43 (N.S)	148.0±27.0
15	122.3±24.5	P< 0.871 (N.S)	113.6±83.5
45	166.0±44.6	P< 0.061(N.S)	242.2±49.9

Table 4.2: Energy (milli Joules) required to pull out tendon from the sheath(absorbable polytrimethylene carbonate suture) Mean +SD, N=4

Time (days)	Control tendon		Operated tendon
5	138.0±4.9	P<0.123 (N.S)	116.0±11.3
15	133.0±25.0	P<0.92 (N.S)	137.0±60.4
45	128.6±7.6	P<0.14 (N.S)	173.0±41.0

Vincular blood supply

Table 4.3 shows the energy which was required for the complete pull out of the tendon from their sheaths at 0, 5, 15 and 45 days. It was evident that in operated groups cutting vinculae had reduced the pull out energy significantly as compared with the control at 5 days after operation.

At 15 days, there was no significant difference between the control and operated foot. This is probably due to reformation of the vinculae.

The mechanical analysis showed a striking difference between the operated and control tendons at 45 days. It was apparent that the high amount of energy and force required for the pull out of the operated tendons was associated with adhesions. This study suggests that in experimental situations, the interruption of vincular blood supply to the tendons is associated with increased adhesion formation and decreased tendon gliding.

Some have speculated that damage to the vincular blood supply of the human tendon severed in no man's land may inhibit its intrinsic healing and increase adhesion formation. Banes et al (1981) have shown that vincular injury decreases the metabolic response of tendon and impairs the healing ability. Matthews and Richards (1976) showed that hypovascular tendons are much more likely to form adhesions than those in which vascularity is preserved. The reason for this differences is not completely clear. There are certainly alternate routes of tendon nutrition, and in many studies the synovial fluid has actually appeared to be the predominant one. The efficiency of synovial diffusion, however, is dependent on motion, and integrity of synovial sheath. Post operative haematoma, immobilisation, and motion limited by pain may all impair these qualities and thus render the nutrition delivered by the

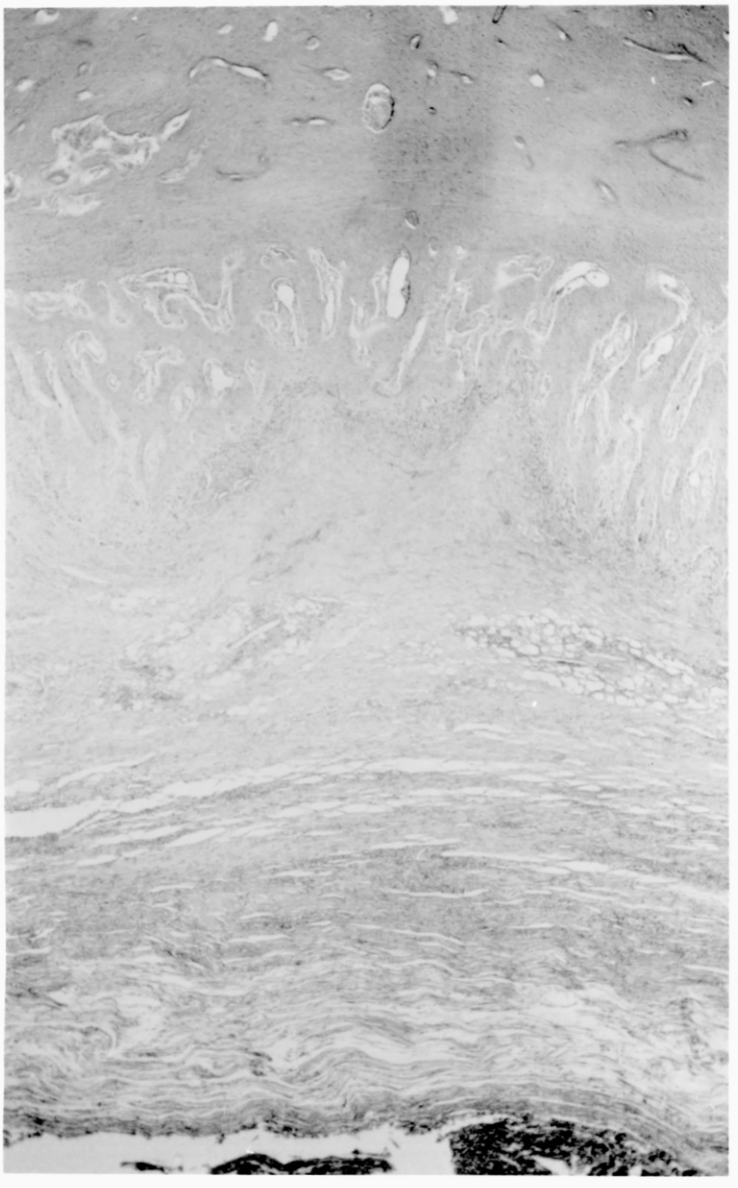
vincular system relatively more important. Under such circumstances, it seems logical that vincular impairment might be the final blow. The mechanical data presented in this study support a positive effect of vincular preservation on the outcome of flexor tendon repair in zone 2. The results showed that if the vinculum longus and brevis of profundus tendon are traumatically divided, the stage is set for considerable adhesions after 45 days if the sheath is excised even if the tendon is intact and mobile.

The mechanical results correlate with histology, showing severe adhesions at 45 days (see fig 4.5). Microscopically, vinculae are much more cellular than tendon and contain a large amount of elastic tissue and have a central arteriole straddled by two venules.

Table 4.3: Energy (milli Joules) required to pull out tendons from their sheath when vinculum longum and brevis were cut

Time (days)	Control tendons	Operated tendons
0	138.2±24.0	0
5	138.25±24.0	64.5±10.6
	P<0.018	
15	138.0±15.5	83.5±44.2
	P<0.059 (N.S)	
45	159.0±11.0	347.0±67.5
	P< 0.009	

Bone



Tendon

Fig 4.5 : Severe adesions at 45 days after excision of the vinculae. D
of the tendon.

4.2.2 Softening test

Suture reactivity: non absorbable polybutester suture

The energy required to pull the suture from the tendon, 3 mm and 15 mm from the suture site both proximally and distally in operated and control foot, is shown in tables 4.4 and 4.5 at 5 and 15 days after operation.

There was no significant difference between the results. This study suggested that inflammatory reaction of the non absorbable suture is not associated with softening.

Suture reactivity: absorbable polytrimethylene carbonate suture

The energy required to pull the suture from the tendon, 3 mm and 15 mm from the suture site both proximally and distally in operated and control foot, is shown in tables 4.6 and 4.7, at 5 and 15 days after operation.

There was no significant difference between the operated and control profundus tendon. This study also suggested that inflammatory reaction of the absorbable suture is not associated with softening.

Table 4.4: Energy(milli Joules) required to pull the suture out of the tendon at 3 mm and 15 mm distal and proximal from the polybutester suture site for control and operated foot after 5 days.

Chicken number	C3mmD	O3mmD	C3mmP	O3mmP	C15mmD	O15mmD	C15mm P	O15mmP
13	57	24	70	19	153	141	213	95
14	40	20	67	46	313	229	242	197
17	14	11	13	3	113	86	110	80
18	14	25	37	29	181	163	114	216
Mean	31.3	20.0	46.8	24.0	190.0	154.8	169.8	147.0
SD(±)	21.0	6.4	26.9	18.0	86.0	59.1	67.4	69.4
P	0.34(N.S)		0.22(N.S)		0.53 (N.S)		0.66(N.S)	

C= control, O=operated, P=proximal, D= distal

Table 4.5: Energy (milli Joules)required to pull the suture out of the tendon at 3 mm and 15 mm distal and proximal from the polybutester suture site for control and operated foot after 15 days.

Chicken number	C3mmD	O3mmD	C3mmP	O3mmP	C15mmD	O15mmD	C15mm P	O15mmP
49	38	21	28	30	197	175	120	91
52	27	44	60	40	135	37	139.5	151
53	14	11	13	35	148.5	86	188	44
54	26.3	25	33	35.5	113	99	110	80
Mean	26.3	25.3	33.5	35.1	148.3	99.3	139.3	91.5
SD(±)	9.8	13.8	19.6	4.1	35.5	57.1	34.7	44.5
P	0.91(N.S)		0.68(N.S)		0.68(N.S)		0.14(N.S)	

Table 4.6: Energy required to pull the suture out of the tendon at 3 mm and 15 mm distal and proximal from the polytrimethylene carbonate suture site for control and operated foot after 5 days.

Chicken number	C3mmD	O3mmD	C3mmP	O3mmP	C15mmD	O15mmD	C15mm P	O15mmP
19	30	50	57	28	180	200	146	140
20	47	54	50	72	190	180	140	178
21	44	62	54.5	70	203	220	137	166
22	42	42	25.5	30	168	240	149	168
Mean	40.8	52.0	46.8	50	185	210	143	163
SD(±)	7.5	8.3	14.5	24	14.8	25	5.5	5.5
P	0.09(N.S)		0.63(N.S)		0.15(N.S)		0.06(N.S)	

Table 4.7: Energy (milli Joules) required to pull the suture out of the tendon at 3 mm and 15 mm distal and proximal from the polytrimethylene carbonate suture site for control and operated foot after 15 days.

Chicken number	C3mmD	O3mmD	C3mmP	O3mmP	C15mmD	O15mmD	C15mm P	O15mmP
55	40	26	64	55	205	205	239	140
58	22	40	50	8	153	227	265	35
59	50	9	17	18	373	75	130	216
60	40	25	17	10	243	169	168	89
Mean	36.0	25	37	22.8	243	169	200.5	120
SD(±)	11.6	12.6	23.8	21.8	93.9	67.0	62.3	77.1
P	0.162(N.S)		0.14(N.S)		0.24(N.S)		0.15(N.S)	

Vincular blood supply

Tables 4.8 and 4.9 show the energy which was required for the complete pull of the suture from the tendon at every 3 mm along the tendon in control and operated feet at 5 and 15 days. There was no significant difference between the operated and the control foot at these periods. This study suggests that interruption of blood via the vinculae plays no role in softening.

Table 4.8: Energy (milli Joules) required to pull the suture out of the tendon, at every 5 mm along the tendon, up to 5 mm above the vinculum longum at 5 days.

	Chicken 7		Chicken 8		Chicken 9		Chicken 11	
	C	O	C	O	C	O	C	O
	22	38	31	41	26	41	27	30
	38	86	60	18	32	21	18	39
	19	28	58	56	23	18	31	26
	25	43	39.5	36	25	40	33	18
	50	16	59.5	40	30	28	24	20
	30	20	48.5	36	43	23	22	34
	45	60	50.5	34	31	32	35	36
	15	44	49.5	38	30	30	26	30
Mean	30.5	41.2	49.6	57.3	30	29.1	27	29.8
SD(±)	12.7	22.9	10.1	10.4	6.0	8.4	5.8	7.8
P	0.236(N.S)		0.059(N.S)		0.641(N.S)		0.60(N.S)	

Table 4.9: Energy (milli Joules) required to pull the suture out of the tendon, at every 3 mm along the tendon, up to 5 mm above the vinculum longum at 15 days.

	Chicken 43		Chicken 44		Chicken 47		Chicken 48	
	C	O	C	O	C	O	C	O
	9	44	74	54	12	19	17	13
	14	26	42	21	32	34	26	43
	22	40	33	29	22	14	33	36
	18	34	25	43	17	21	28	29
	46	39	35	82	20	20	30	34
	35	33	44.5	45.8	26	23.6	23	47
	45	38	40.5	40.5	14.5	26.5	27.6	30.1
	23	34	48.5	50.5	20.6	20.5	22.6	36.2
Mean	26.3	36	42.8	45.8	20.5	22.3	25.9	33.5
SD(±)	13.9	5.5	14.6	18.3	6.4	5.9	4.5	10.3
P	0.104(N.S)		0.717(N.S)		0.425(N.S)		0.057(N.S)	

Inflammation of the tendon as a part of healing process.

The energy required to pull out the suture from the tendon at 3 mm and 15mm distal and proximal from the cut surface is shown in table 4.10 and 4.11 at 5 days and 15 days.

The mechanical analysis showed a significant difference between the control and operated foot at 3 mm proximal at 5 days. It was apparent that the low amount of energy and force required for the pull out of the operated tendon was associated with softening. However, no significant difference was observed between the control and operated at 3 mm distal.

Macroscopic examination showed that the stumps retract an average distance of 1 cm. The space so formed between the stumps is partly filled with new tissue which generates from the end of the stump. From an early stage it was apparent that the process of regeneration in the region where the stumps join the new tissue is different at the proximal and distal stumps. The generation of new tissue at the proximal part is more than that at the distal part (see fig 4.6). This is probably due to the vascularity of the tendon. The distal part is situated in the vascularized zone whereas the proximal part is in the avascular zone (see fig 4.7). This study showed that softening is associated with generation of the new tissue and it is more extensive at the avascular segment of tendon.

Microscopic examination, however, showed that at 5 days, the tendon stump contained an increasing number of cells distinct from those in the original stumps (see fig 4.8). At the point of junction of the stumps with the new tissue the fibroblasts do not lie parallel to the long axis of the tendon but are irregularly arranged. They were frequently at right angle to the long axis, i.e.

parallel to the cut ends of the tendon. After 15 days, some of the cells near the junction of the new tissue and the old stumps take a cartilage like appearance,

having rounded nuclei and plentiful irregular cytoplasm and resting in a matrix which is highly metachromatic.

Presumably this orientation is becoming a fibrous sheath, or covering, over tendon end, not the link to the other stump. If there was a repair, the tension across it would cause cells to orientate across the gap, i.e. parallel to the tendon axis.

Mechanical tests correlate with histology.

Table 4.10: Energy(milli Joules) required to pull the suture out of the tendon at 3 mm and 15 mm distal and proximal from the cut end for control and operated foot after 5 days.

Chicken number	C3mmD	O3mmD	C3mmP	O3mmP	C15mmD	O15mmD	C15mm P	O15mmP
61	42	13	30	9	100	150	178	145
65	25	16	30	5	127	165	151	152
66	22	17	46	8	24	115	225	158
67	31	25	35	13	150	149	157	125
Mean	30	17.75	35.3	8.6	100.3	144.8	177.8	145
SD(±)	8.83	5.12	7.54	4.1	54.7	21.1	39.6	14.35
P	0.119(N.S)		0.007(N.S)		0.100(N.S)		0.099(N.S)	

Table 4.11: Energy (milli Joules) required to pull the suture out of the tendon at 3 mm and 15 mm distal and proximal from the cut end for control and operated foot after 15 days

Chicken number	C3mmD	O3mmD	C3mmP	O3mmP	C15mmD	O15mmD	C15mm P	O15mmP
68	13	12	26	32	87	144	212	113
69	34	43	29	36	115	159	215	179
72	30	18	19	48	98	88	97	147
73	11	28	18	34	81	128	180	169
Mean	22	25	23	37.5	95.75	129.75	176	152
SD(±)	11.7	13.5	5.3	7.1	14	30	54	29
P	0.640(N.S)		0.075(N.S)		0.106(N.S)		0.49(N.S)	

Proximal



Distal



Fig 4.6: The generation of the tissue at proximal and distal part

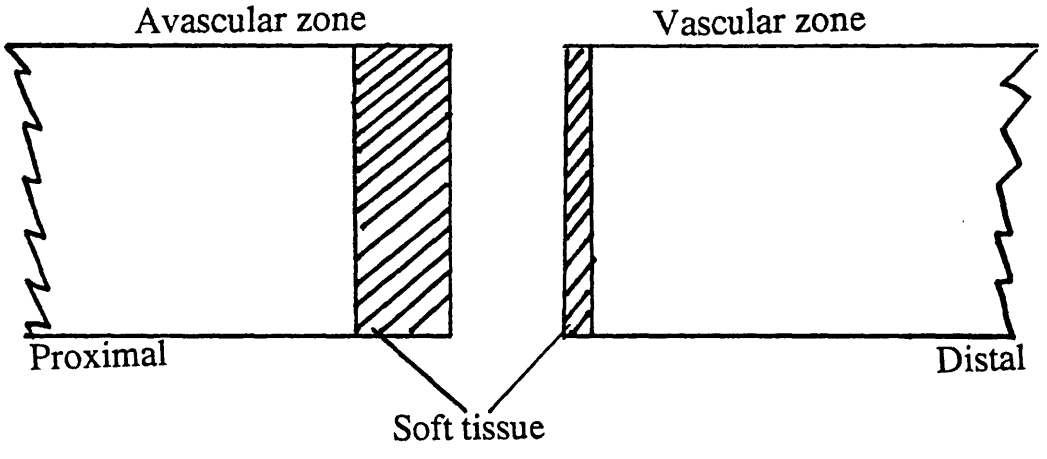


Fig 4.7: Diagram of the position of the softening

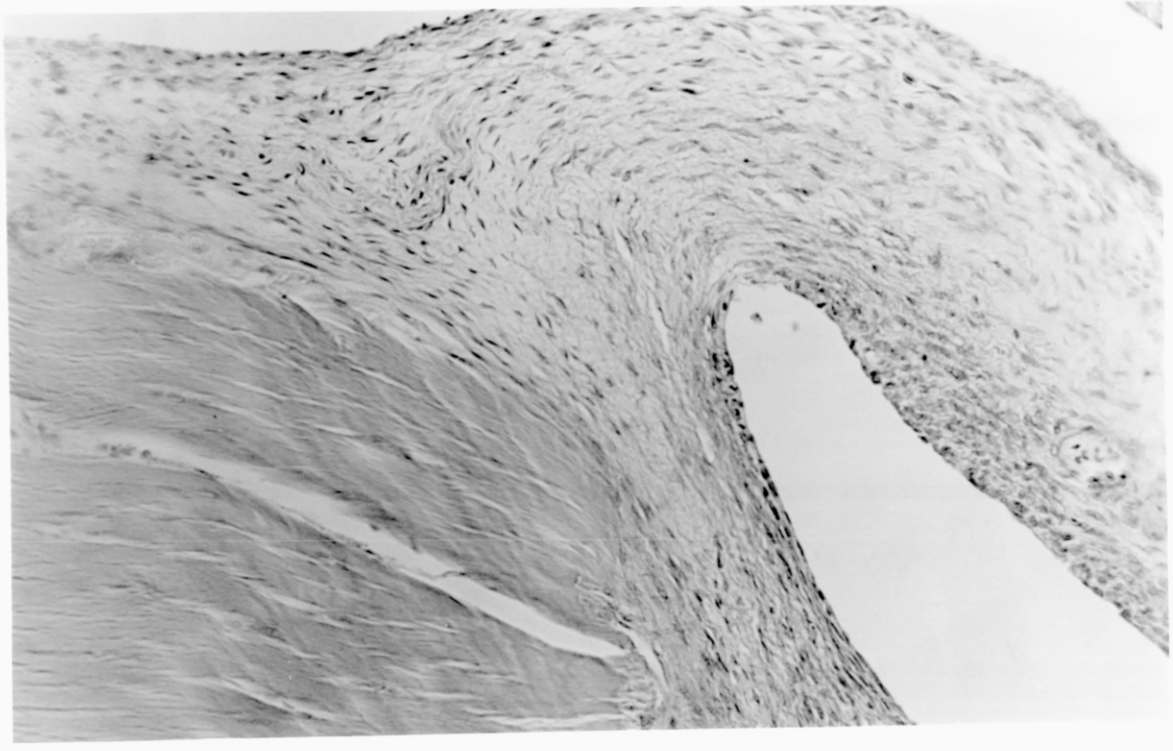


Fig 4.8: Microscopic examination of the tendon stump at 5 days when the stump was transected (after 5 days)

Chapter 5: Variation of holding strength of flexor tendon sutures with time

5.0 Introduction

A wide range of suture materials have been produced, but few of them are good for tendon repairs. Collagen based absorbable lose their strength too rapidly, so the repair would come apart before tendon has united. Synthetic polymer non absorbables suffer from factors such as low tensile strength or excessive elongation. Stainless steel overcomes these problems, but is difficult to handle.

This study examines the potential use for two new suture materials, absorbable polytrimethylene carbonate (Maxon, Davis and Geck, USA) and non absorbable Polybutester (Novafil, Davis and Geck, USA) for tendon surgery. polybutester was chosen because it represents a typical non reactive polymer suture, similar to Prolene, and therefore it is a control to compare against polytrimethylene carbonate. Polytrimethylene could possibly be good because of high initial strength and the possibility of the tendon becoming clear of suture. But the problems with this suture are loss of strength and reactivity when absorbed. The aims of this chapters are:

1) To examine post operative repair strength with time, to check whether there is a "danger period" when the sutures have lost their strength and the tendon ends have not yet united properly.

2) To compare histologically, the tissue reactions to sutures .

These should lead to a recommendation as to whether these suture materials are suitable for tendon repairs. If they are satisfactory from the mechanical and histological aspects, then they may become popular in tendon surgery generally, displacing the awkward stainless steel sutures currently used.

5.1 Methods and materials

5.1.1 Experimental subjects

Chicken was chosen as experimental subject as described in section 4.1.1

5.1.2 Caging and feeding

Caging and feeding was carried out as described in section 4.1.2.

5.1.3 Design of operative group

A minimum of six chickens per group was advised. Four were used for tensile testing and two for histology. This was essentially a mechanical study, although specimens were used for histology for correlation with the mechanical findings. The experimental groups chosen were:

Group I, transected tendons repaired with non absorbable polybutester.
Group II, transected tendons repaired with absorbable polytrimethylene carbonate.

5.1.4 Pre- operative preparation

Pre-operative preparation was carried out as described in section 4.1.4.

5.1.5 Operative technique

Transected flexor profundus tendons were repaired in the third toe of

chickens using absorbable polytrimethylene carbonate or non absorbable polybutester suture material. The chickens were anaesthetised with a mixture of Halothane, nitrous oxide and oxygen as described in section 4.1.4. A mid lateral incision was used to expose the sheath. The sheath was excised longitudinally through a one centimetre incision at the level of the Second and third phalanx. The flexor digitorum profundus was exposed and sharply transected with a number 15 blade mid way between the vinculum longus and brevis (see fig 5.1). This area was found to be a vascularized zone (chapter 2) and tendon tends to heal much quicker in this area. The tendon was then repaired using a simple square core stitch of 5-0 Polytrimethylene carbonate/polybutester and six interrupted peripheral stitches of 6-0 polytrimethylene/polybutester. Initially it was intended to use the modified Kessler technique, but since locking loops do not contribute to strength, they were eliminated (see chapter 3). The skin was closed with 4-0 Polybutester. The operated foot was placed in plaster and the left leg acted as control.

5.1.6 Immobilisation

The middle toe was flexed about mid-position and a small ball of absorbent cotton placed in the hollow of the foot. Gauze bandage was then applied to hold the toe in this flexed position and was carried up to the bare point of the leg. This was not a bulky bandage; otherwise the foot would move too much in it. Elastoplast was then applied over the bandage, forming a club shaped plaster (see fig 5.2) incorporating the third toe and maintaining it and the foot in a moderately flexed position on the lower leg. The bandage should not be carried out too high, otherwise the muscular part of the thigh is irritated when the chicken is walking.

Three time intervals were chosen for sacrifice of the animals, 5, 15, and 45

days. These times were chosen because they follow softening, adhesions, and reconstruction (Mason and Allen, 1941). Most of the flexor tendons of the hand have gained enough tensile strength to begin motion after 45 days. Immediately prior to sacrifice the plaster was removed. No anaesthetic was necessary. If the chicken's head was covered loosely with a green towel it lay quietly while the plaster was removed.

5.1.7 Post mortem examination

The post mortem examination was carried out as in section 4.1.6.

5.1.8 Histology

Histology was carried out as in section 4.1.7.

5.1.9 Biomechanical analysis

The wound was reopened and the sutured tendon examined. The gross amount of reaction was noted. Adhesions were qualitatively graded as absent, mild, moderate or severe. Notes were also made about the healing process and suture material. The repaired tendon was then removed intact and clamped in an Instron machine (model 1122). Sutured tendons were tested by extending them in the machine until failure. Tests were carried out in the air at room temperature at a crosshead speed of 20 mm/ min. The specimens were kept moist with Ringer's solution throughout, to prevent changes due to dehydration. The suture materials were not removed before testing the strength, although in one instance one or two interrupted sutures had broken. The measurements given therefore record the strength of the tendon repair tissue plus that added by the sutures. It was believed that with this method a truer idea of the clinical situation could be gained.

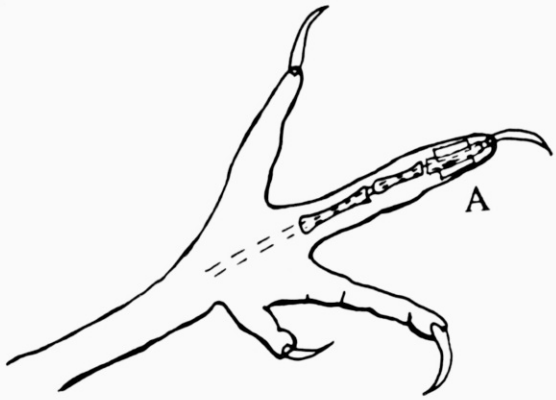


Fig 5.1: Diagram of the site of operation: Site A received a cut

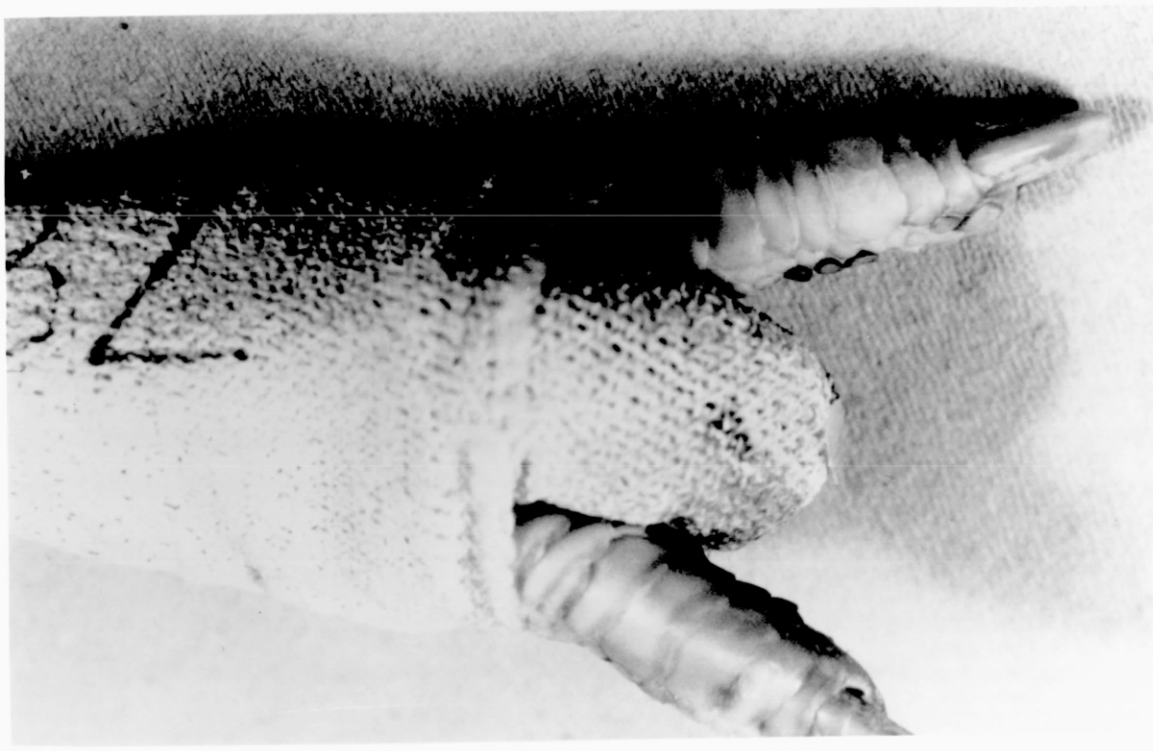


Fig 5.2: The method of immobilising the chicken foot

5.2 Results and discussion

5.2.1 Macroscopic and microscopic details of sutured tendons

The detailed descriptions of the tendons examined macroscopically when polytrimethylene carbonate (Maxon) and polybutester (Novafil) was used at 5, 15, and 45 days are given in tables 5.1a, 5.1b, 5.1c and 5.2a 5.2b, 5.1c. Each specimen was given a score using following criteria:

Excellent results

1) Smooth inner surface of the wall of the tendon sheath.
2) Healed tendon junction according to time interval
3) Absence of adhesion
4) Unimpaired gliding of tendon within the sheath

Good results

1)Minimal or filmy adhesion
2) Little to no impairment of tendon glide within the sheath

Fair results

1) Adhesion between the tendon and the overlying sheath wall
2) Some interference of the excursion of the tendons within the sheath

Poor results

1) Tendons bound to surrounding structures by massive adhesions
2) Minimal gliding of tendons within the sheath area
3) Rough inner lining of the sheath wall at repair site

Table 5.1a: Macroscopic appearance of polybutester sutured tendon at 5 days

chicken	Macroscopic appearance
110	This was a fairy satisfactory suture and the tendon ends were still united by suture material. The tendon stumps were swollen, lost their natural colour and appeared pink or red instead of white. The gap between the stumps was filled by a red gelatinous exudate, which could be easily scraped. The suture material seen lying on the surface of the tendon. No adhesions observed. The tendon glided easily in the sheath. Score: Good
111	A nice approximation was obtained. The gap was bridged across by fibrous tissue. The tendon stumps were swollen, lost their natural colour and appeared red. Mild adhesions were observed and the tendon appeared to glide easily through the surrounding tissues. The suture material was seen surrounded with inflammatory tissue. Score:Good
112	The macroscopic appearance was practically the same as that described in chicken 110.
113	There was a gap of 2 mm and suture pull out of the tendon.

Table 5.1b: Macroscopic appearance of polybutester sutured tendon at 15 days

chicken	Macroscopic appearance
77	A good end to end suture was obtained. The tissues at site of suture were less inflamed than before. The redness noted previously was replaced by healthy pink. The adhesions between the tendon and surrounding tissue were quite loose. The tendon stumps were fused to rather fibrous appearing tissue which bridged across the interval left by separation. The sheath was partly fused to stumps and intervening tissue but the outer layer was less dense and allowed some movement of the new tendon. The suture material was slightly covered by the new fibrous tissue. Score: Fair
79	A good union was observed. The gap between the stumps was filled by a fusion of the fibrous tissues. The sheaths had also fused with stump. The stumps could not be separated without tearing up some adhesions. The suture material was slightly covered by new fibrous tissue. Score: fair
78	The area of the suture was easily uncovered and was not adherent to the sheath. The tendon stumps were held together by a thick fibrous strand in which the suture was embedded. The whole region was covered by glistening membrane, under which or through which the tendon moved. Score: Excellent

81 The tendon stumps had separated approximately 2 mm and were united by rather thin looking young connective tissue in which were embedded the two bits of tendon. Moderate adhesion had formed between the suture line and surrounding tissue. Some interference of the excursion of tendons within the sheath was observed. The suture material was covered by the new fibrous tissue.
Score: fair

Table 5.1c: Macroscopic appearance of polybutester sutured tendon at 45 days

chicken	Macroscopic appearance
95	The tendon was apparently quite adherent to the sheath and the sheath securely attached to the bone so that no motion was transmitted. The sutures were visible and the cut ends of the tendon were not bulbous. Score: poor
96	A good union was observed. Most of the swelling subsided, and the tissues were regaining their normal appearance. Mild adhesions were found between the sheath and the tendon. Tendon glided easily within the sheath. Over the suture line, there was seen a thin layer of fibrous tissue which could be easily removed from the tendon. The stumps had not yet regained their natural colour and the suture material was easily identified at the repair site. Score: good
97	A satisfactory end to end suture was obtained. Examination showed a few adhesions between the site of suture and the surrounding tissues. The sheath covered the newly formed tissue uniting the stumps, and the new tendon glided freely within the sheath. The stumps had not yet regained their natural colour and the suture material was easily identified at

the repair site.
Score: good

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98 A good end to end suture was obtained. The tendon glided freely beneath the sheath. The sheath could be opened fairly easily, except for a few loose adhesions which bound it to the tendon. Healing took place beautifully and except for slight transverse greyish pink or grey discolouration the line of apposition of the stumps could not be detected. The suture material was still visible at the repair site buried within the tendon stumps.
Score: good

Table 5.2a: Macroscopic appearance of polytrimethylene carbonate sutured tendon at 5 days

chicken	Macroscopic appearance
106	There was separation of one millimetre and the suture had pulled out of the tendon. Both stumps were somewhat enlarged, the proximal more than the distal. Moderate adhesions between the site of the suture and the surrounding tissue were observed. Score: poor
107	The cut surfaces remained in good contact. The tendon appeared to glide easily through the surrounding tissues. The tendon stumps were swollen, lost their natural colour and appeared red. The suture materials were surrounded by red inflammatory response. The region of operation was seen to be moderately free from adhesions. Score: good
108	A good end to end suture was obtained. The tendon stumps were swollen, lost their natural colour and appeared red. An acute inflammatory response was observed. Over the suture line there was a thin layer of fibrous tissue which could be easily removed from the tendon. Mild adhesions were observed and tendon glided easily in the sheath. The suture material was visible at the site of the repair. Score: good

109 The macroscopic appearance was practically the same as that described in chicken 108.
Score: good

Table 5.2b: Macroscopic appearance of polytrimethylene carbonate sutured tendon at 15 days

chicken	Macroscopic appearance
83	A good union was observed. The tissues at the site of the repair were less inflamed than before. The adhesions between the tendon and the sheath were quite loose. The gap had been bridged by fibrous tissue. The suture materials were seen surrounded by fibrous tissue and the colour of the suture had faded. Score: good
84	The tendon stumps were held together by a thick fibrous strand.The sheaths had also fused by stumps. The stumps could not be separated without tearing up many adhesions. The suture material was seen lying on the surface of the tendon. Score: Fair
86	A good union was observed. A good functioning tendon was found which glided easily beneath a sheath. The region of operation was seen to be moderately free from adhesions. The suture material was not visible. Score: good
87	The stumps had separated. The tendon was quite adherent to

the sheath and the sheath securely attached to the bone. No motion was transmitted. The suture material was embedded within the fibrous tissue.

Score: poor

Table 5.2c: Macroscopic appearance of polytrimethylene carbonate sutured tendon at 45 days

chicken	Macroscopic appearance
100	Both stumps were bulbous and thicker than normal. the adhesions between the tendon and surrounding tissue were quite severe. The sheath was fused to the stumps and intervening tissues. The outer layer of the sheath was dense and did not allow movement of the new tendon. Suture material were absorbed and undetectable to the naked eye. Score: poor
101	The tendon stumps were bulbous probably more so than the polybutester specimens at 45 days. Moderate adhesions were observed. Sheath tissues were still adherent to the stumps. No suture material was visible at this stage. Score: fair
102	The bulbous stumps and the thickened mass of tissue in the gap were firmly adherent to the adjacent bone, allowing no motion. Suture material was not visible. Score:poor
103	The macroscopic appearance was practically the same as chicken 100. Score: poor

The detailed histological findings of sutured tendon with polytrimethylene and polybutester at 5, 15, and 45 days are shown in tables 5.3a, 5.3b, 5.3c and 5.4a, 5.4b, 5.4c.

Table 5.3a: Fine details of Polybutester sutured tendon at 5 days

chicken	Microscopic appearance
114	Microscopic examination of the cross section of the proximal stump showed it to be badly disrupted by the suture materials. The tendon itself showed no evidence of proliferation, although the nuclei were slightly larger than normal. An increase in vascularity was noted. The fibrous septa were thicker than normal. The sheath was thickened and was fused to the tendon. The gap was filled with granulation tissue. The distal stump showed practically no changes. An acute inflammatory response consisting of polymorphonuclear leukocytes, macrophages and lymphocytes was seen encompassing the suture material.
115	Microscopic examination of cross section of the proximal stump showed considerable disruption of the tendon fibres, evidently due to trauma of suturing. There was considerable thickening of the fibrous septum and sheath, and in places it was quite difficult to be certain that areas that looked like fibrous tissue were not in fact proliferating tendon. The gap

tissue was granulation and fibrous tissue, presumably from the sheath and peritendinous tissue. Polybutester suture at 5 days was surrounded by a slight irregular zone of inflammatory cells, consisting of polymorphonuclear leukocytes, macrophages and lymphocytes.

Table 5.3b: Fine details of Polybutester sutured tendon at 15 days

chicken	Microscopic appearance
76	Microscopic examination showed that the nuclei in the proximal stump had increased considerably in number. This increase was noted at the tip of the stump, but they were also present well up the stump. The increases in vascularity and fibrous septum proliferation noted in early specimen were also seen here. From some parts of the end of the stumps, young tendon fibrils and nuclei could be seen to push distally into the gap. The sheath about the stumps was thick and ran continuously from one stump to the other. The gap between the two stumps was filled by a rather dense fibrous tissue. In general, the tissue were lined up in rows parallel to the line of pull of the tendon, though the closer one approached the distal stump, the less definite this orientation became. The distal stump also showed a considerable increase in the number of nuclei especially at the tip; it passed over imperceptibly into the gap tissues. The fibrous septa were more nuclear and thicker than had been noted before in the distal stump. Polybutester sutures at 15 days were surrounded by a band of fibroblastic cells which had begun to orient around the periphery of the suture. A narrow band of macrophages and a few degenerate cells were seen at the interface between the reaction zone and the tendon, The suture reaction is judged as slight.

80 Microscopic examination showed that the gap had been bridged across by the sheath and peritendinous tissues which had fallen into the gap and formed a dense strand from stump to stump. The tendon itself in the proximal stump showed evidence of proliferation throughout the whole area of the section. The increase in the number of nuclei was so great that the collagen fibres were either obscured or had disappeared. At the end of the stumps nuclear become much more numerous and the tendon fibres less and less distinct. The distal stump showed approximately the same picture as the proximal, except that it was not so far advanced.

The suture reactivity was slight as described in chicken 76.

Table 5.3c: Fine details of Polybutester sutured tendon at 45 days

chicken	Microscopic appearance
74	Microscopic examination showed the proximal stump to be very nuclear, especially towards the tip. The sheath over the stumps was quite thickened, well attached to the stump and had taken a longitudinal arranged structure parallel to the line of pull of the tendon. It passed over the end of the stump into the gap and took part in the formation of the intervening tissues. The septum under the proximal stump was very thick and vascular, and it too continued into the gap for a certain distance as a dense structure capable of withstanding tendon pull. The gap tissues were dividing into longitudinal rows of nuclei and fibres and resembled tendon. The distal stump had the same histologic appearance as the proximal. Polybutester suture at 45 gays was surrounded by a thin band of proliferating fibroblasts and reaction was minimal.
99	The stumps were packed with nuclei, and the tendon fibres were not visible towards the tip. The sheath was not as thick as in early specimen. The suture material was surrounded by a thin band of proliferating fibroblasts, but this was not as marked as specimen 74. The gap tissue was divided into longitudinal rows of nuclei and fibres and resembled tendon.

Table 5.4a: Fine details of polytrimethylene carbonate sutured tendon at 5 days

chicken	Microscopic appearance
73	A longitudinal section through the whole specimen showed the union of two stumps affected by proliferated sheath tissues, which passing over the stumps, dipped into the gap and formed there a dense strand. In this strand the fibres and nuclei were lined up in rows. The proximal stump showed an increase in number of nuclei in scattered areas throughout, and at the end of the stump the tendon fibres were seen to pass into a triangular zone of tissue which covered the tip and lay between proliferating sheath tissues which dipped down about the stump to lie in the gap. The septa of the tendon were also thickened and more cellular than normal. The distal stump showed some proliferating changes. The sheath about the tendon was thickened and dipped over the end of the stumps into the gap, where it fused with proliferative sheath tissues from the proximal stump. There was an acute leukocytic infiltration about the polytrimethylene suture.
75	The microscopic examination was the same as in chicken 73 .

Table 5.4b: Fine details of polytrimethylene carbonate sutured tendon at 15 days

chicken	Microscopic appearance
82	In the proximal stump, the fibrous septa were thick and nuclear. Many mitotic cells were seen. The tendon itself was much more nuclear than normally, especially towards the tip, where the nuclei were so numerous as to obscure the collagen fibres. At the end of the stumps, the tendon tapered off gradually, still maintaining its increase in nuclei, and fused imperceptibly with the gap tissue. Suture material embedded in stumps was still surrounded by inflammatory infiltration with associated giant cells. The absorbable polytrimethylene suture still appeared to be somewhat more reactive than polybutester at 15 days. The nuclei were increased in number, fatter and more vascular than normal, and numerous mitoses were seen. The distal stump also showed evidence of tendon cell proliferation, especially about the periphery, where it had fused with the gap tissues. The sheath about the stumps was thick and vascular and fused with the gap tissue.
85	Proximal stump was very nuclear through its whole length, and its fibres were arranged in long rows parallel to the line of tendon pull. towards the distal end the stump began to taper off and to become continuous with the gap tissues. The polytrimethylene carbonate suture had caused considerable commotion in the stump and there was still a great deal of inflammatory reaction, and foreign body giant cells were

common. The blood vessels were more plentiful than in normal tendon. The normal fine connective tissue septa were also wide and cellular. The sheath was thickened and dense, with its nuclei and fibres flattening out and lining up along the line of pull. The gap tissue uniting the stumps was made up of cells and fibres from sheath, from peritendinous tissues and from the stump. Towards the distal stump polytrimethylene carbonate suture and its knot had made a defect in the replacement tendon. There was here a small area of inflammatory infiltration. The distal stump showed the same appearance as the proximal.

Table 5.4c: Fine details of Polytrimethylene carbonate sutured tendon at 45 days

chicken	Microscopic appearance
104	Microscopic examination showed that the proximal stump was more nuclear than normal tendon, and showed one particularly bulbous area a short distance proximal to the tip into which the tendon bundles passed, spread out fan like and became exceedingly nucleated. Distal to this bulbous enlargement the width of the tendon gradually decreased. The suture in this bulbous area had begun to dissolve and was surrounded by an irregular zone of inflammatory cells, consisting of macrophages, giant cells, and scattering neutrophils. The nuclei in the stumps were somewhat larger and more oval than in normal tendon and were lined up in longitudinal rows parallel to the line of the tendon. The fibrous septa in the most proximal part of the stumps were thickened. There was increased vascularity of this stump. The tissue between the stumps looked like very nuclear tendon tissues. It was lined up in the longitudinal bundles, was quite nuclear and moderately vascular. The distal stump, which was continuous with the intervening tissues, had the same histologic character as the proximal.
105	The stumps, while exceedingly nuclear, were beginning to show a more definite alignment of the nuclei and fibres. They were directly continuous with the gap tissues, which were arranged

in fibrous bundles as normal tendon.
The place through which the suture passed was quite bulbous, and about the polytrimethylene carbonate was considerable infiltration with white blood cells and occasional giant cells. Where suture material (knot) lay against the end of the tendon, the tendon fibres stopped abruptly; in other places the tendon passed imperceptibly into the gap tissues.

The examination of the microscopic as well as the macroscopic specimens of tendon sutures showed that there may be considerable variation between specimens. The rate of healing in some chickens may be quite rapid, while in the others it may be slow, in some the amount of sheath proliferation may be excessive and so far overshadow the actual tendon cell proliferation that the latter appears unimportant. In some instances, the amount of inflammatory reaction around the suture material was so great as to make the suture, especially polytrimethylene carbonate suture, a failure, or nearly so, while in the others, the disposition of the suture within the tendon and the presence of the knots between the ends of the tendon seriously interfered with healing.

At the time of operation, however, some difference in handling properties of polytrimethylene carbonate and polybutester sutures were noted. Polybutester was easy to knot and glided easily through the tendon, whereas polytrimethylene adhered somewhat to surrounding tissues and instruments, slightly increasing drag as the suture was placed through the tendon.
Five days after operation, examination revealed a considerable amount of swelling around the tendon for both polytrimethylene and polybutester repair.

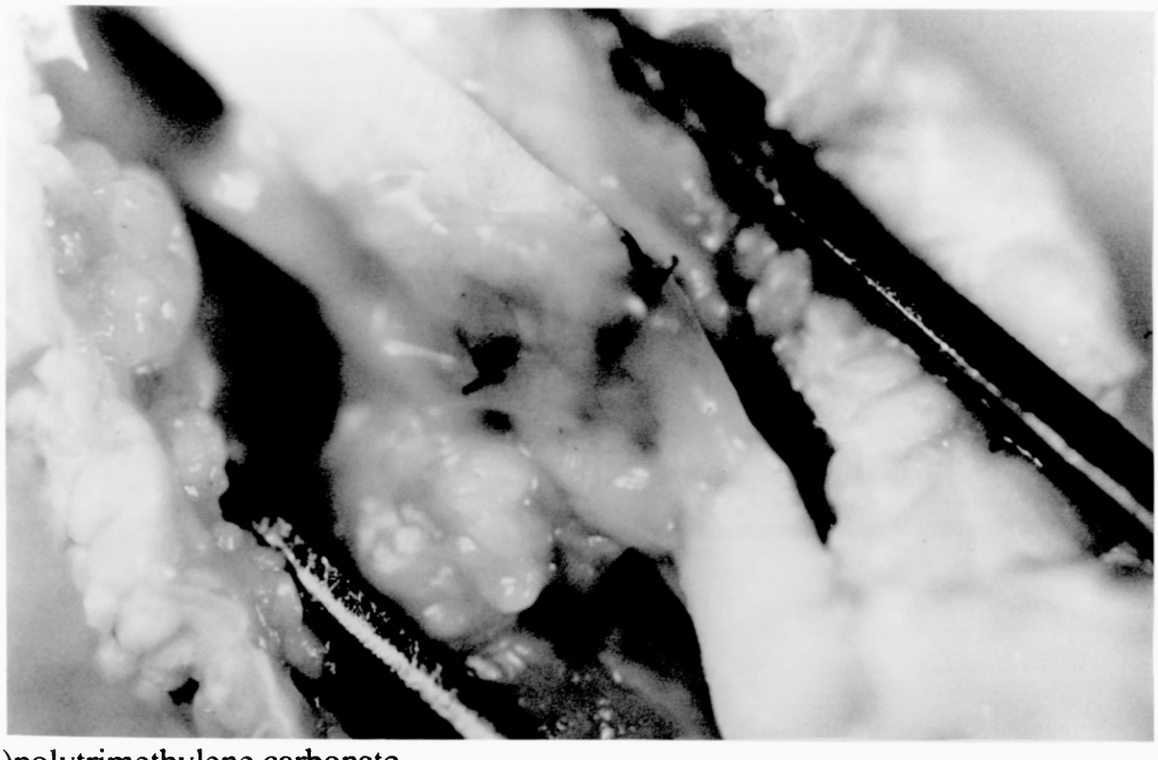
The tendon stumps were swollen and lost their natural colour and appeared pink or red instead of white (see fig 5.3a and 5.3b). This colouration was probably due to the hyperaemia within the tendon, as it was evidenced by the fine longitudinal red striations, which can be seen if the tendon is magnified. An acute inflammatory response consisting of polymorphonuclear leukocytes, macrophages, and lymphocytes was seen encompassing the suture materials. The amount of inflammation was slightly more around the polytrimethylene suture (see fig 5.4a and 5.4b).

The tendon architecture in most animals was grossly distorted by the surgical trauma and subsequent oedema in both the polytrimethylene carbonate and polybutester repairs. The gaps between the stumps were filled by red gelatinous exudate which could be easily scraped out. This had no tensile strength, did not hold the stumps together, and any function at this time must have been due to the suture holding the stumps. The stumps in few cases could not be separated without tearing up a few adhesions and the suture material was seen surrounded by red inflammatory tissue in both polytrimethylene and polybutester repair within the tendon stumps.

Microscopic examination showed that both distal and proximal stumps were slightly thicker than normal. This enlargement was not only due to the presence of suture material but to actual proliferative changes in the tendon itself. i.e. the collagen fibres were being spaced apart by a proliferation of cellular material, fibroblasts, as a precursor to laying down collagenous repair tissue across the gap and to heal the trauma within the tendon stumps caused by the suturing. There was a great increase in the number of the tendon nuclei.

Variation of holding strength of flexor tendon sutures with time.

a)Polybutester



b)polytrimethylene carbonate

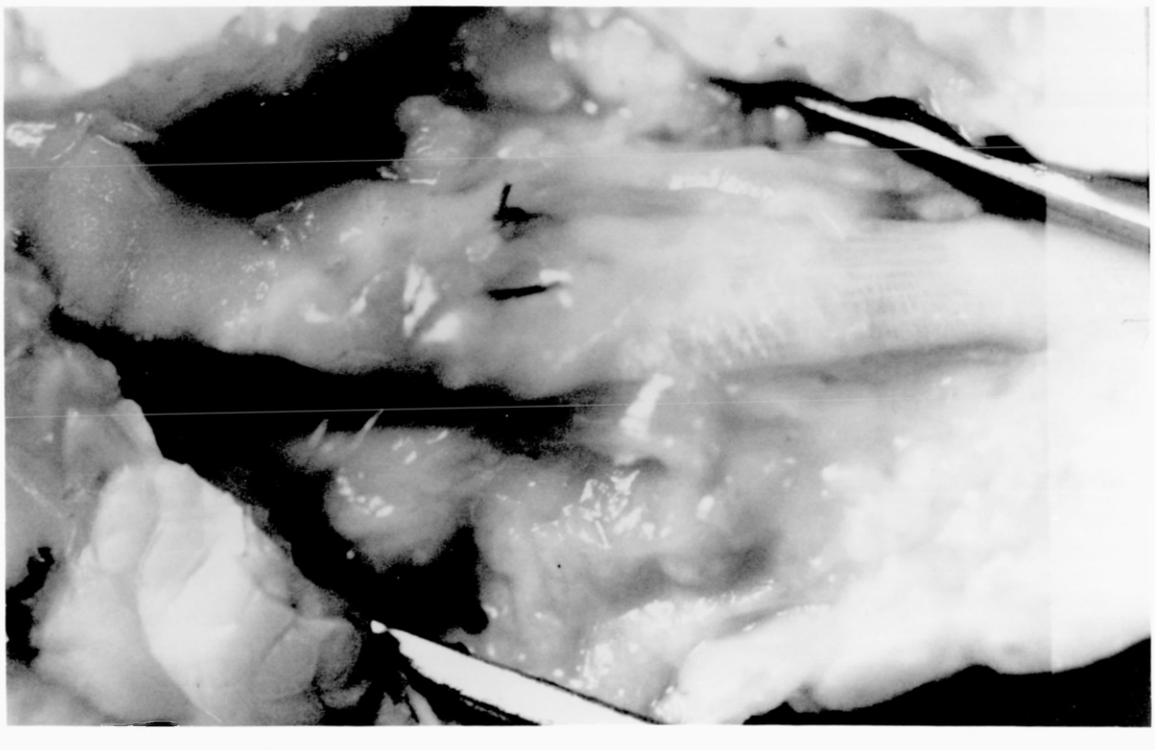


Fig 5.3: Macroscopic appearance of the sutured tendon (5 days)

Variation of holding strength of flexor tendon sutures with time.

a)Polybutester



b)polytrimethylene carbonate



Fig 5.4: The inflammatory response around suture (5 days)

The increase, while especially marked near the tip of the stumps, was also present in strips and zones at some distance from the suture line. The tips of the stumps were beginning to send out tiny strands of fibres and nuclei into the intervening tissue by 5 days. At this time tendon appeared very vascular and the fibrous septa throughout both stumps were thicker than normal.

At 15 days, the tissue at the site of the suture was definitely less inflammatory than before in both polytrimethylene and polybutester repairs (see fig 5.5a and 5.5b). The redness noted previously was replaced by healthy pink. The adhesions between the tendon and the sheath were moderate and could be broken up easily by blunt dissection. The sheath was fused to the stumps and intervening tissues in both the polytrimethylene carbonate and polybutester repairs, but the inner layers were loose and allowed some movement of the new tendon.

Microscopic study of both polytrimethylene and polybutester repairs at this time showed definite advances over the conditions at 5 days. This advancement affected especially the tendon stumps, the participation of which in the bridging of the gap was considerably increased. They showed a marked increase in nuclei, not only at the ends, but throughout the stump. Where the stumps abutted the intervening tissues they sent out long strands of fibres which passed proximally from the distal stump and distally from the proximal stump.

The suture material within the stump was still the site of some inflammation, but this was more in polytrimethylene than polybutester (see fig 5.6a and 5.6b), presumably because the inert polybutester was being encapsulated in a fibrous sheath, whereas the polytrimethylene was still being degraded (and phagocytosed) by the host tissues, hence maintaining an inflammatory

response.

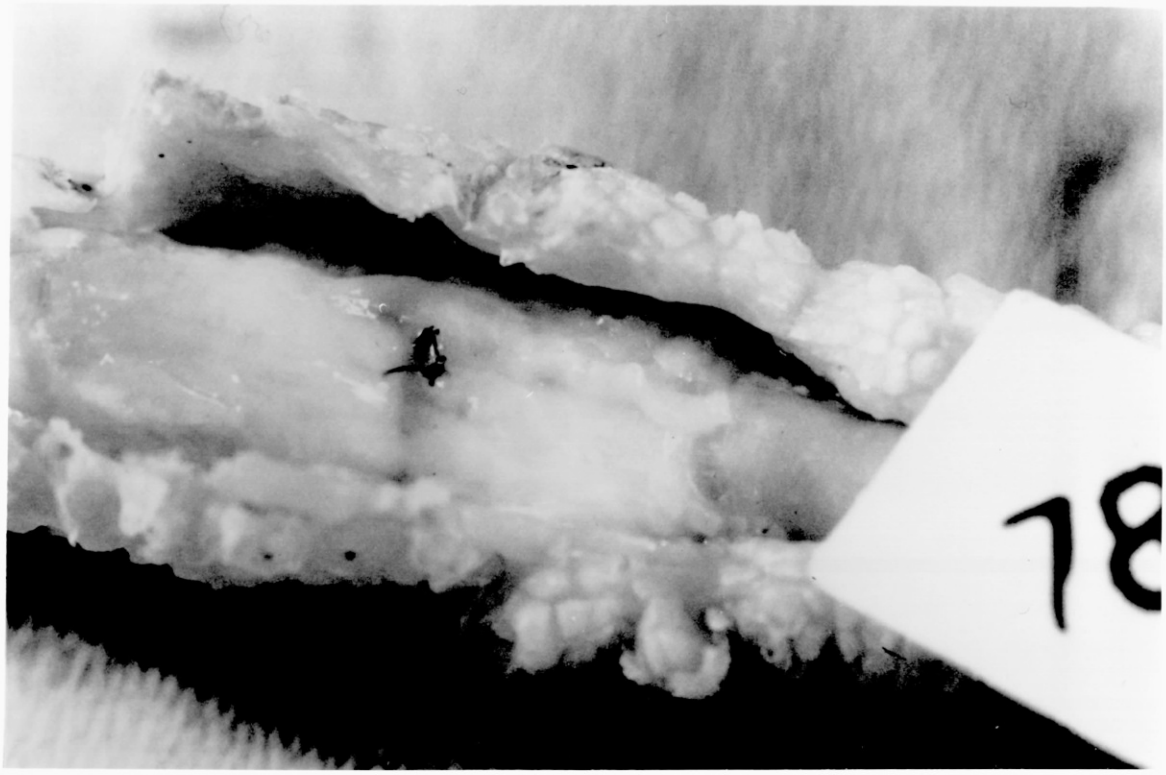
After 45 days, the union was substantially due to the tendon itself. When the suture was uncovered, moderate to severe adhesions were found between the sheath and the tendon for both the polytrimethylene carbonate and polybutester repairs. Most of the swelling had subsided, and the tissues were regaining their normal appearance in case of polybutester repair (see fig 5.7a). The suture was easily identified at the site of the repair at all time intervals with non absorbable polybutester. In the case of polytrimethylene carbonate repairs, stumps were still bulbous and thicker than normal (see fig 5.7b). This enlargement was due to high tissue reactivity of suture within the tendon. This swelling prevented easy gliding of the tendon within the sheath.

Microscopic examination showed that the stumps were still very nuclear. and mitoses were frequent, but the marked proliferation noted at 15 days was not present. It was not possible to determine the point where the stump ended; instead there was a continuity of similar collagenous tissue stretching from stump to stump. This tissue was oriented in line with the pull of the tendons, and there was some suggestion that it was beginning to form into fibre bundles. Numerous longitudinal blood vessels were present in this newly formed tendon tissue. The sheaths were still thick, but were beginning to separate from the tendon, especially in polybutester repairs, though still adherent by many fine strands. However, in the case of polytrimethylene repairs, the sheath was more adherent to the tendon.

The tissue reactivities of polytrimethylene and polybutester suture at 45 days are shown in fig 5.8a and 5.8b. The tissue responses were judged to be slight to minimal for polybutester suture and high for polytrimethylene suture. The cellular responses were found only in the vicinity of the implant site in polybutester repair, whereas in polytrimethylene repair it was more

Variation of holding strength of flexor tendon sutures with time.

a)Polybutester



b)polytrimethylene carbonate

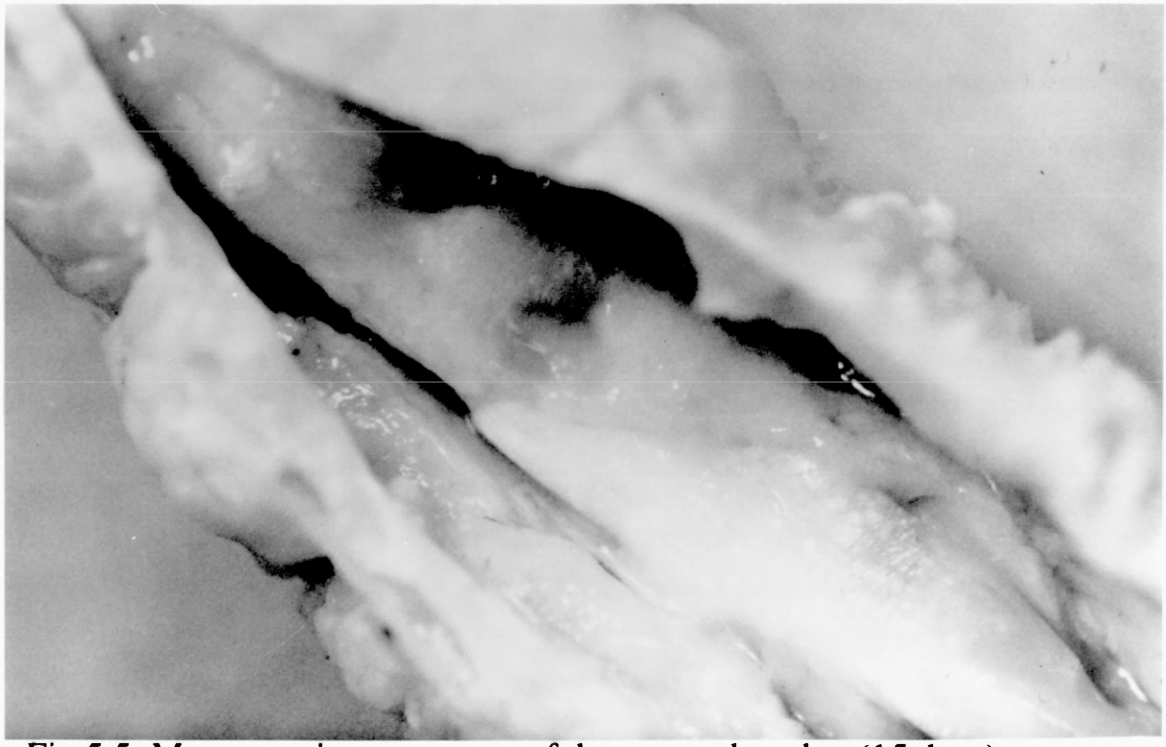


Fig 5.5: Macroscopic appearance of the sutured tendon (15 days)

a)Polybutester



b)polytrimethylene carbonate

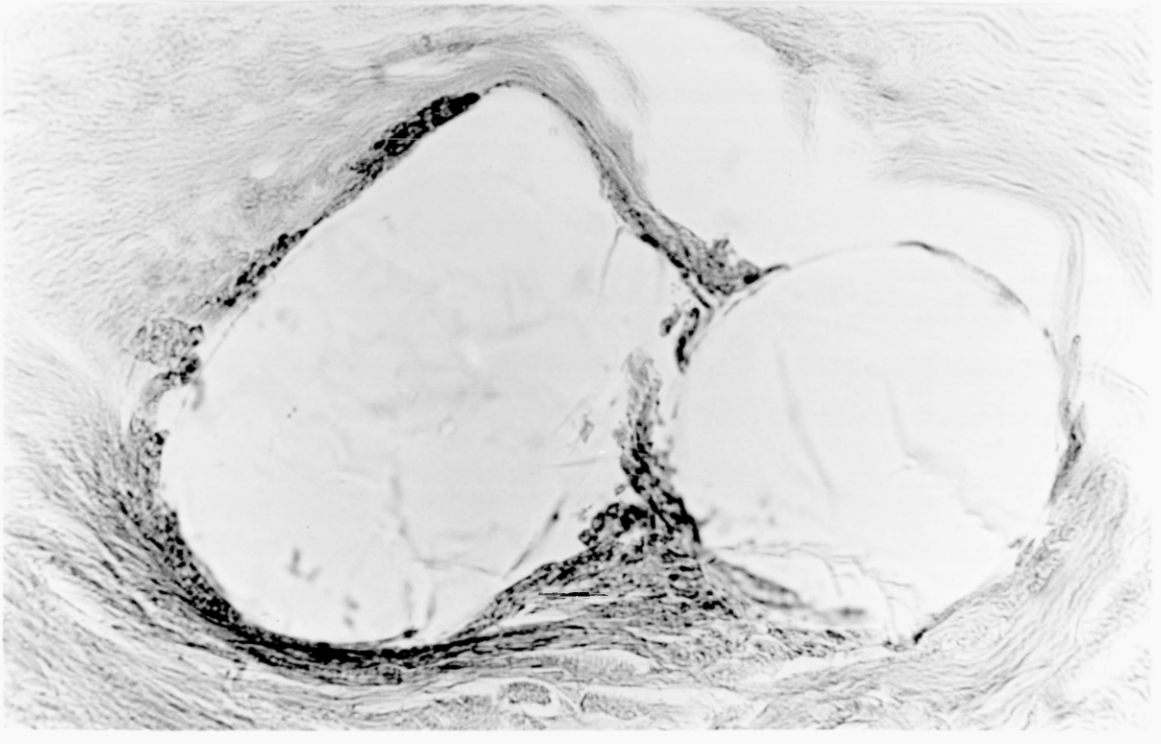


Fig 5.6: The inflammatory response around suture (15 days)

a)Polybutester



b)polytrimethylene carbonate

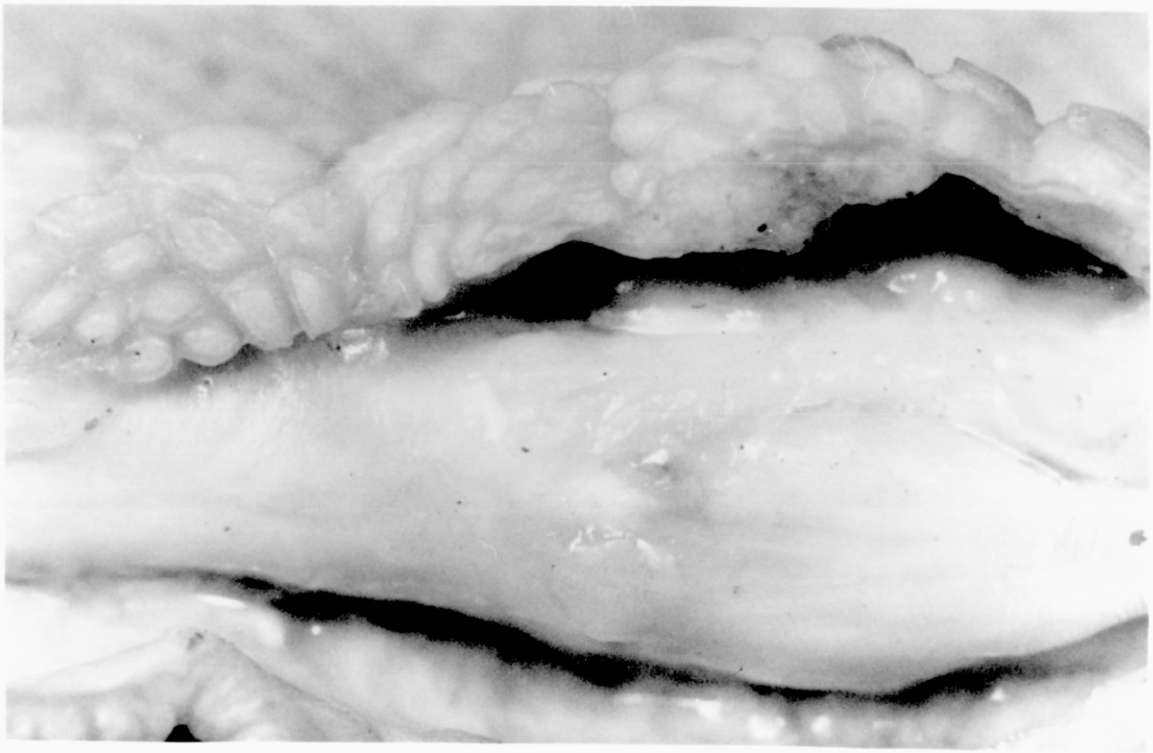


Fig 5.7 Macroscopic appearance of the sutured tendon (45 days)

Variation of holding strength of flexor tendon sutures with time.

a)Polybutester



b)polytrimethylene carbonate

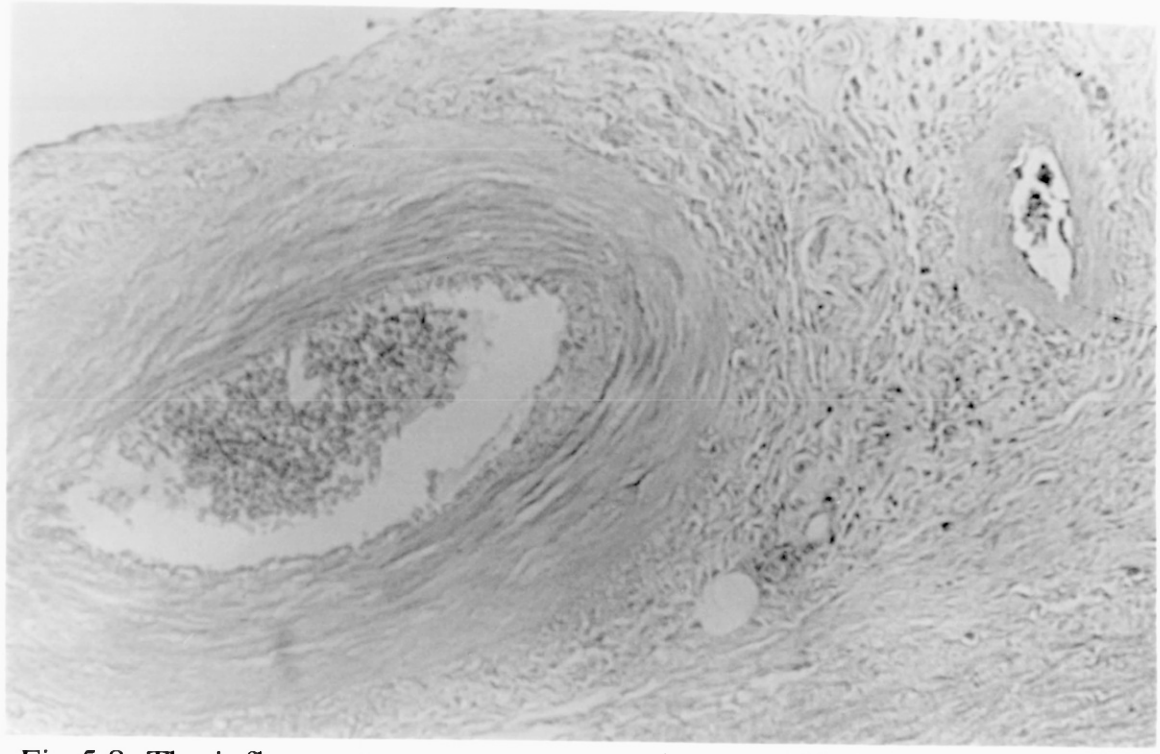


Fig 5.8: The inflammatory response around suture (45 days)

widespread, where the sutures were being absorbed. This high tissue reactivity caused the bulbousness of the tendon and prevented easy gliding of the tendon in the sheath. It was concluded, therefore, that differences in suture material can affect the results of tendon repair by post surgical inflammation.

5.2.2 Mechanical testing of sutured tendon

The results of polytrimethylene and polybutester repair at 5, 15, and 45 days are shown in table 5.5 and 5.6.

At 0 days, Polytrimethylene was significantly stronger than polybutester ($p < 0.039$).
At 5 days, the strengths of both polybutester and polytrimethylene repair were very low, and certainly much lower than the holding power of the tendon for the suture at 0 days. The strength of the union at this time, slight as it was, was due to suture, but this strength was lower than the tested holding power of the fresh tissues for the suture. We could assume, therefore, that the healing process in the tendon was associated with softening of the tendon. Not only were the tissues across the line of union without any effective strength, but the efficiency of the sutures themselves was very much diminished by the softening (the polybutester repairs lost 54% of initial strength and polytrimethylene repairs 67%). However, at this stage, no significant difference was found between the polybutester and polytrimethylene repair ($p < 0.592$). The suture pulled out of the tendon in all cases.

At 15 days, the strength was beginning to rise for both the polybutester and polytrimethylene repairs. Not only did the initial separation require greater force, but the sutures occasionally broke, as they did in fresh tendon. At this

time striking evidence was seen of the value of the surrounding tissues which had formed a solid cuff about the stumps. In 5 days specimens, this tissue was soft and easily ruptured, at 15 days it presented itself as a definite entity which was adherent to the stumps and bound them together. When separation occurred, this cuff of surrounding tissue stripped away from one of the stumps and remained attached to the other. The cuff presented in most cases; but, in the earlier stages it was quite soft and usually broke irregularly. At 15 days, polytrimethylene repairs were significantly stronger than polybutester repairs ($p< 0.015$). This is probably due to greater initial strength of the Maxon suture.

At 45 days, both polytrimethylene and polybutester repairs had high tensile strength, with no significant difference ($p< 0.661$) between the groups.

Although polytrimethylene carbonate maintained its strength sufficiently long to allow good physical union of divided tendon, the high tissue reactivity during its dissolution did adversely affect the surrounding tendon tissue and, hence, the functional results.

However, because of good strength, ease of handling, slight or minimal tissue reactivity, a possible advantage may exist for the use of polybutester suture.

Table 5.5: Strength of polybutester repairs at 0, 5, 15, and 45 days

chicken	Day	Rupture forces (N)	Mean ±SD
	0	9.5	
	0	8.5	9.87±1.49
	0	12.0	
	0	9.5	
110	5	5.0	
111	5	6.0	4.5±1.73
112	5	5.0	
113	5	2.0	
77	15	16.0	
78	15	14.0	14.0±1.73
79	15	13.0	
81	15	13.0	
95	45	33.0	
96	45	53.0	44.0±8.3
97	45	46.0	
98	45	45.0	

Variation of holding strength of flexor tendon sutures with time.

Table 5.6: Strength of polytrimethylene carbonate repairs at 0, 5, 15 and 45 days

chicken	Day	Rupture forces (N)	Mean ±SD
	0	17.0	
	0	15.0	15.75±1.96
	0	13.0	
	0	18.0	
106	5	3.5	
107	5	5.0	5.17±1.96
108	5	8.0	
109	5	4.2	
83	15	22.0	
84	15	21.0	19.12±2.95
86	15	18.0	
87	15	15.5	
100	45	57.0	
101	45	43.5	42.87±10.1
102	45	36.0	
103	45	35.0	

Chapter 6: Conclusions

The aim of this investigation have been considered in five parts.

1) Review of the literature to examine tendon suture technique, tendon suture materials, adhesion between repair and surrounding tissue, weakening of repair due to softening, and tendon healing and blood supply.

2) To study the main similarities and differences between the flexor tendons, pulleys, sheath, vinculae and vascular structure of the chicken and human finger.

3) To investigate in some detail the features of suturing techniques which influence their holding power. This could relate to suture itself, such as diameter or surface roughness, or else to the layout of the stitches, such as locking loops, criss crosses, and placing the suture in different layer of the tendon. To use the knowledge thus gained to try to design an improved suture method.

4) To investigate the effects of various factors on softening and adhesions, such as: deleterious tissue reaction to suture material, vincular blood supply, inflammatory changes within tendon as part of healing process, and correlate histological analysis with mechanical testing.

5) To test two new suture materials for tendon suturing and produce a graph of post operation repair strength variation with time, to check whether there is a "danger period" when the sutures have lost their strength and the tendon ends have not yet united. If they are satisfactory from the mechanical and histological aspect, then they are likely to become very popular in tendon suturing.

Review of the literature showed that despite the tremendous investigative efforts in the areas of flexor tendon anatomy, biomechanics, nutrition, healing, adhesion formation and softening, return of satisfactory digital performance following tendon interruption remains one of the most difficult and challenging problems for hand surgeons. Controversy persists with regard to the technique of the repair, suture material, adhesions and softening. Although some recent reports of digital performance following flexor tendon repair appear to show considerable improvement over those of previous studies, there can be no question that, for most hand surgeons, flexor tendon repair in zone II still represents a difficult and frustrating problem.

The study of the blood supply of the tendon showed that there are 3 vascular systems of different origin. The proximal system originates from a vincular like structure at the distal part of the iv phalanx. An intermediate system originates from the vinculum longum at the distal end of the iii phalanx. A distal vascular system originates from vinculum brevis. This conforms to the general pattern observed in man with apparently avascular zones in the tendon between these areas.

The analysis of the blood supply of the chicken's flexor tendon has contributed greatly to improving techniques for management of acute flexor tendon injuries. Study of the blood supply of the flexor system showed that exact knowledge of the vascular or avascular zones is important when considering tendon healing. Caplin (1975) showed that if the lacerated site is in the poorly or avascularized zone, the tendon heals slowly, and requires 6 to 8 weeks of controlled mobilisation, whereas in the vascularized zone, it is only needed for 3 to 5 weeks and tendon heals much quicker. Most of the previous investigators that used the chicken as a model did not specify the location of the lacerated site and various results have been reported. It seems that placing the suture in vascular or avascular zones may have caused variation in results between previous studies. Theories of tendon adhesions and softening are based on these

concepts.

With regard to tendon suturing , mechanical testing demonstrated a significant difference in grasping strength in the epitenon and within the tendon fibres. Placing the suture in the tendon fibres gives 83% more strength than if the peripheral stitches are placed in the epitenon layer. This finding contributed greatly to design of the stronger suture technique, where high physical loads are often increased by early mobilisation.

The mechanical testing and multiple x-raying method also showed clearly that the locking loop tendon sutures do not produce a repair which is stronger than a simple transverse stitch when using fine suture material. The locking elements require more operative manipulation of the tendon, which probably causes adhesion. Since locking loops collapse at low loads, suture techniques which depend on locking loops will, often lead to gap formation at low loads and hence poor results. It was concluded that the quest for a consistently good suturing technique (i.e one which would sustain a larger force before the start of gap formation at the repair site) would involve designing a stitch which would not include locking loops as the main load bearing elements.

When the criss cross stitch was subjected to load, it converted into a single loop by longitudinal separation of tendon fibres, which eventually allowed disruption of the repair. The criss cross sutures did not grasp or lock onto a bundle of fibres.

The above information was put together and a new suturing technique was designed. The new technique was chosen for tendon repair for the following reasons:

1) The new technique, by achieving anchorage wholly within the tendon fibres, has greater strength with regard to 2 mm gap and ultimate rupture.

2) Multiple passes, particularly in running configuration, share the load and

hence multiply the strength of suture material used. The peripheral stitches alone are as strong as the widely used Kleinert modification of the Kessler with an over and over circumferential stitch and core stitch.

3) The technique also minimises suture material on the surface of the tendon, which should reduce foreign body reaction where adhesion formation is known to occur.

4) The point at which suture material grasps the surface is 5 mm away from the cut ends. This is important because there is softening in the tendon adjacent to cut ends following injury.

5) The technique presents a smooth junction, which is not thicker than the normal tendon., thereby allowing easy gliding within the sheath. Eversion of the edges of the cut tendon end is avoided by passing the suture through the epitenon close to the ends.

The important difference between the suturing method presented here and the range of preexisting methods tested for comparison is that it is the only one in which the transverse passes across the tendon fibre direction are into the tendon fibres . The traditional horizontal mattress and Halsted method take the opposite path, but were originally designed for wound closure and intestinal anastomoses, rather than tendon repair . It has has been shown recently that the Halsted peripheral stitch was significantly stronger than the commonly used "over and over" stitch, but that work was done before it was known that stitches are held more securely within tendon fibres rather than in the epitenon layer. Since the holding power of both peripheral and core stitches with this technique is stronger than the sutures, which always snapped rather than pulling out, the only remaining avenue for increasing the repair strength is to have more passes of suture and/or stronger suture material. Since, also, the deep transverse passes are easily inserted and allow the running configuration to draw the tendon ends together, it was felt that there was no reason to use

complex locking features such as those described by Savage.

The new stitch has not yet been tested in vivo, therefore the effect of biological processes on the tendon repair technique is not known. We also have not studied its effect on intrinsic tendon healing. However, on the basis of mechanical testing reported in this thesis, the new technique appears to be superior to other methods for tendon suture .

With regard to adhesions and softening, it was also found that if the vinculum longus and brevis of the profundus tendon were traumatically divided, the stage would be set for considerable adhesions after 45 days if the sheath is left open, even if the tendon is intact and mobile. This study suggested that the interruption of vincular blood supply to the tendon is associated with increased adhesion formation and decreased tendon gliding. This showed the importance of the blood supply. This study also suggested that the presence of suture material alone is not a contributory factor to adhesion, even when a reactive suture material such as Maxon was present. It was found that inflammatory reaction of the absorbable and non absorbable suture is not associated with softening. The blood supply via vinculae also plays no role in softening.

Transection of the tendon, caused inflammatory changes within the tendon as part of the healing process. From an early stage it was apparent that the process of inflammation in the region where the stump joined the new tissue was different at the proximal and distal stumps. The inflammation at the proximal part was more than that of the distal part. This was due to vascularity of the tendon: the distal part was placed in the vascularized zone whereas the proximal part was in the avascular zone. This study showed that softening was associated with inflammatory changes within tendon as a part of the healing process and it is more extensive at the avascular zone of the tendon. This contradicts the finding of peacock (1959) who stated that an avascular tendon

undergoes cell death and collagen degeneration, resulting in a soft, weak tendon. The new suture technique designed will minimise the disastrous strength losses after operation by placing the peripheral stitches well away from the cut ends.

This thesis also examined the the potential use for two new suture materials, absorbable Polytrimethylene carbonate (Maxon) and non absorbable polybutester (Novafil) for tendon surgery. These materials were chosen because Novafil represents a typical non reactive polymer suture which is similar to Prolene and therefore it is a control and can be compared against Maxon. Maxon could possibly be good because it has high tensile strength and the possibility of the tendon becoming clear of sutures, however loss of strength and reactivity when resorbed could create problems. The tissue responses were judged to be slight to minimal for non absorbable Novafil and high for Maxon suture. Mechanical testing showed that both sutures had good strength and that Maxon could keep its strength long enough to unite the tendon ends. However, high tissue reactivity of Maxon during its dissolution is a main disadvantage. Tendons remained bulbous even after 45 days and gliding within the sheath was prevented. However, because of good strength, ease of handling, and slight or minimal tissue reaction, a possible advantage may exist for Novafil sutures in hand surgery.

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