This is to certify that this thesis, "Experimental Production of Tendon Sheaths", is my own work and has not been submitted to any other University for a degree.

H.Gaylis.

H. Gaylis

# EXPERIMENTAL PRODUCTION OF TENDON SHEATHS

An Experimental Study, using Venous Grafts in
Cercopithecus aethiops (Blue vervet monkey)

A Thesis submitted to the Faculty of Medicine,
University of the Witwatersrand, Johannesburg,
in partial fulfilment of the requirements for
the Degree of Master of Surgery
by
H. GAYLIS

June 1953.

"<u>Praying Hands</u>" Albreght Durer

"The restoration of damaged tendons in the fingers is one of the most baffling problems in Surgery".

Alexis Carrel.

To my Mother

# PREFACE

> "Is there any thing whereof it may be said,
> see this is new? It hath been already of
> old time, which was before us"
>
> Ecclesiastes 1.10.

This thesis, primarily an experimental attempt to reconstruct tendon sheaths using venous grafts, was well under way when information came to hand indicating that Leo Mayer, one of the pioneers of modern tendon surgery, had utilised this tissue forty years previously in experiments on the prevention of tendon adhesions. Aware of the disappointing results in the use of venous grafts as reported by Mayer, the author was not deterred and the experiment was continued, for not infrequently two workers engaged on a similar line of investigation produce conflicting results. It is the presence of so many variables such as the species of animals used, the methods and techniques employed and the interpretation and assessment of results that largely account for the discrepancies.

In a sense, this experiment might be considered negative, in that it failed to achieve what it set out to do. Having assessed the preliminary results, a fleeting sensation of frustration and disappointment was experienced, due largely to the denial of that immediate satisfaction that comes from the visible result of a practical task well done. With the passage of time it was soon appreciated that a negative thesis could have almost the same value as a positive thesis. Certain new facts have emerged while certain other observations have corroborated the findings of previous workers.

Despite the ups and downs which inevitably accompany any research, and there are many, it is gratifying to realise that one is much the richer for the experience. One has had to familiarise oneself with animal and laboratory methods, acquaint oneself with the fundamentals of photography and physics, drawing and statistics, and last but not least learn the art of thinking and writing, an accomplishment coveted by so many, but mastered by so few.

The evolution of a thesis is seldom the labour of one man. He that can accomplish the task without the assistance of his fellowmen is indeed a genius. Therefore not only am I dutifully bound, but take great pleasure in expressing my indebtedness to those of my colleagues and associates who assisted me.

First and foremost I am indebted to Professor W.E. Underwood who was instrumental in securing a Nuffield grant to aid this project. His interest and suggestions were a constant encouragement.

I wish to express my sincere appreciation to Dr. James Murray of the South African Institute for Medical Research for the animals placed at my disposal, and the laboratory facilities afforded me, to Dr. B.J.P. Becker and Dr. N.S.F. Proctor of the Department of Pathology of the University of the Witwatersrand for guidance in the interpretation of the histological sections, to Dr. F. Brandt also of the Medical Research, for the preparation of the histological sections, most of which involved a difficult and laborious technique, to Professor A.E.H. Bleksley, Head of the Department of Applied Mathematics of the University of the Witwatersrand for assistance in the statistical analysis of the results, to Mr. J.C. Allan who assisted me with many of the experiments and often gave me valuable advice, to Miss Dick and her staff of the Medical School Library, University of the Witwatersrand for their sincere co-operation, and to Mrs. D. Leahy who undertook the typescript and showed unfailing enthusiasm in her work.

To widen the scope of this thesis, one of the original intentions was to attempt a statistical survey of tendon injuries in the Witwatersrand area. Exhaustive enquiries from prominent and reputable Insurance Companies revealed that the pertinent data was not available. (Appendix A). Similar enquiries were made in Great Britain with little satisfaction. (Appendix B). In fact one major Accident Corporation with world wide ramifications reported that it was not their "practice to statiscise accidents or injuries into different groups, and we have not the means at our disposal of extracting the information your desire." Thereupon, the information was sought from the United States of America. (Appendix C). In this respect I wish to acknowledge with thanks the information received from Mr. William L. Connolly, Director of the United States Department of Labour and his permission to publish statistics relevant to hand injuries.

Progress in industrial medicine will only be achieved with the establishment of detailed fact finding systems, involving the recording and analysis of the causes and prevention of accidents, and the assessment of the various methods of treatment and rehabilitation. In this respect the United States has made notable strides, but in fairness to other countries one should not lose sight of the fact that she has the advantage of her immense wealth.

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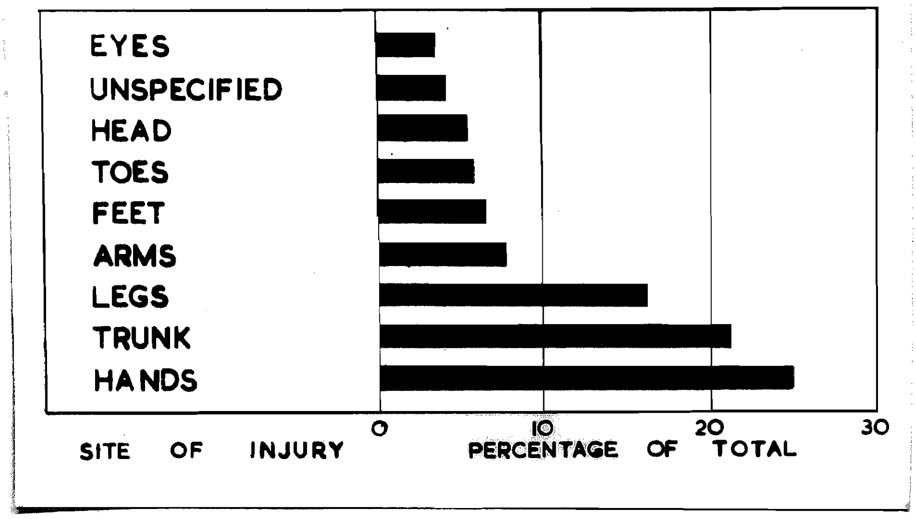


Fig. I The relative incidence of injuries to the body in industrial occupations

Note the high incidence of hand injuries. This analysis was prepared from statistics abstracted from the "Annual Bulletin of The Statistical Department of the Industrial Commision of Wisconsin" (1949). During this period there were 26,615 compensable injuries of all types, of which 6,559 or 24.6% were hand injuries. Hand injuries alone accounted for the loss of 418,224 working days or an average of 63 days per case. The expense involved in compensation and treatment was 1,992,043 dollars or an average of 269 dollars per case. Analysis of Statistics issued in 1951 by the Industrial Commissions of New York State, California, Illinois, Georgia, Virginia and Pennsylvania reveal a similar high incidence of hand injuries relative to other injuries.

# CHAPTER I

## INTRODUCTION

> "The hand of the working man is his most valuable asset. Without it life becomes a burden"
>
> Kanavel

### THE HAND AND INDUSTRY

This paper, though esentially concerned with the problem of tendon injuries, would not be complete without reference to the hand itself, a region which must be considered as a functional whole.

In this highly mechanised industrial era, so appropriately referred to as the "Age of Trauma" by Bunnell, the hand which controls our machinery and manipulates our tools is constantly exposed to the hazards of injury and infection. It is not surprising then, to learn that the hand heads the list of industrial accidents. In fact, in the United States of America, injuries of the hand account for 20% to 40% of compensable injuries. The vulnerability of the hand to injuries can be readily appreciated by reference to Figs. I and 2.

In highly industrialised areas the number of working days lost to industry and the nation, the expense involved in compensation and rehabilitation, and the disability suffered by the injured is staggering.

### THE HAND AND DISABILITY

To the manual worker the hand is of vital importance, for upon its integrity depends his very livelihood. Although the disability is only in part and the rest of the man intact, he is not always able to compensate for the loss. A permanent disability is often a major catastrophe, for too frequently he has to change to another occupation and few vocations exist where the services of the hand can be spared. Re-employment is difficult and should he learn a new trade he usually receives less remuneration and gravitates from skilled

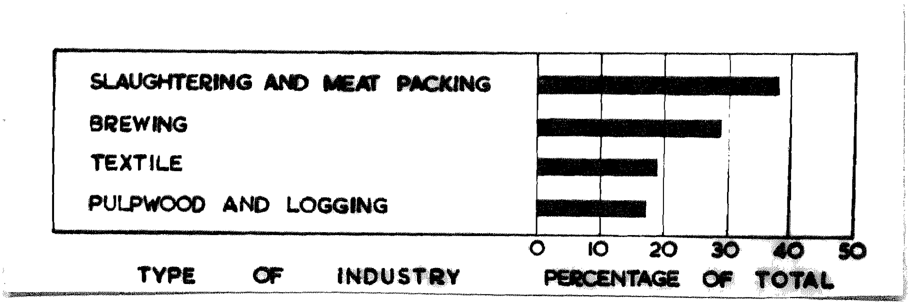


Fig. 2 Comparative incidence of hand injuries in different industries

Note the high incidence of hand injuries in the slaughtering and meat packing industry - an occupation in which sharp tools or instruments are extensively utilised. This analysis was prepared from statistics abstracted from the "Bulletin of the Eleventh Annual Congress of Industrial Health", Atlanta, Georgia (Feb. 1951).

to unskilled labour. With his disability he is in danger of further injury and may lose confidence in his skill and in himself.

Since the introduction of compensation laws, great strides have been made in the prevention of injuries. The installation of safety devices, the periodic inspection of personnel, machinery and tools, and the establishment of first aid units have all greatly contributed towards this end. While progress has been made in reducing the overall accident rate, a parallel reduction in the percentage of hand injuries has not been noted. Furthermore, and most distressing is the fact that hand injuries result in permanent partial disabilities more so than any other type of injury. (Carr 1951).

The United States Bureau of Labour Statistics reported that of the 23,700 manufacturing workers who experienced permanent disabilities in 1948, 18,000 or 77% were injuries to the hand or fingers. During 1949, the Bureau reported that the corresponding figures were 19,200 permanent injuries, of which 14,500 or 76% were hand disabilities. It is evident that although the total number of permanent disabilities to manufacturing workers was reduced by 19%, the proportionate ratio of hand injuries was reduced by only 1%.

## REASONS FOR THE HIGH INCIDENCE OF PERMANENT DISABILITY FOLLOWING HAND INJURIES

The high incidence of permanent disability following hand injuries is readily understood if one appreciates that the hand, although composed mainly of strong material, includes machinery of perfect refinement and tissues of great delicacy and specialisation.

An injury to the hand seldom involves an isolated tissue. Associated damage to nerves, tendons, bones, joints and skin is common. The correct treatment requires the combined basic knowledge of the Neuro-Surgeon, the Orthopaedic and the Plastic Surgeon. For the three specialities to work together or in series is obviously undesirable or even impracticable. The treatment of an injured hand should, therefore, be undertaken by one well trained in the fundamentals of the three specialities, and not delegated to one inexperienced or junior in position. Pulvertaft's statement (1948), that "there can be few fields of surgical endeavour today where a new consciousness of responsibility is more needed than in the treatment of hand injuries" is most timely. Unfortunately too few surgeons are sincerely interested in this vital problem; perhaps due to the fact that the results of hand surgery are not dramatic, the work is painstaking and monotonous and the life of the patient seldom in jeopardy.

Further progress will only be made when the hand is considered as a regional problem. In this respect a notable advance has been made in the United States, where under the leadership of Bunnell a speciality of hand surgery has arisen under the direction of the American Society for Surgery of the Hand.

## TENDON INJURIES

The restoration of function to tendons, following trauma or inflammation to the gliding mechanism, presents one of the many unsolved surgical problems. Indeed, Alexis Carrel once stated that he considered the restoration of damaged tendons in the fingers one of the most baffling problems in surgery. Mason (1940) stated that severance of flexor tendons in fingers and hands generally resulted in disability. Cootes (1941) had "never heard of a case where a flexor tendon divided in its digital sheath had been restored to usefulness by suture." Teece (1943) in an experience covering several hundred cases of tendon injuries had never seen a case of successful primary or secondary suture when the point of division was within the flexor sheath. Brebner (1946) in a personal communication expressed a similar viewpoint. Despite the pessimistic attitude sometimes expressed concerning the possibility of successful repair of flexor tendons divided within the digital sheath, good results have been secured, but rarely with consistency. Notable examples are the results reported by Miller (1942), Posch (1948), and Pulvertaft (1948). However, the fact that so few published results are available, is an accurate indication of the disappointing outcome of flexor tendon suture.

The increasing use of tendon grafts for the repair of tendons injured within the digital theca, is further testimony to the unsatisfactory results of primary or secondary suture. Sumner Koch (1951) in a personal communication, stated that "unless we can carry out tendon suture under absolutely favourable conditions and immediately after injury we wait until the inflammatory reaction has disappeared and then, instead of attempting to suture the tendon within the digital sheath, we invariably remove the tendon from the digital sheath and replace it with a tendon graft." The results of the well followed and completed study of 138 cases of tendon grafting in 118 patients presented by Boyes (1950), is a creditable performance and holds out great promise for this method of treatment. In 25% of his cases flexion of the finger was complete as indicated by the ability of the pulp of the finger to touch the distal crease of the palm; in 50% the pulp reached to within one-half inch of the distal crease of the palm.

On the other hand, division of extensor tendons generally yields good results by immediate or delayed suture, or even by effective immobilisation without suture. A Bantu patient under the author's care received an incised wound over the base of the thumb with division of the extensor pollicis longus tendon. He presented for treatment two days after the injury, and the wound appeared infected. The thumb, wrist and forearm were immobilised in a plaster cast and the patient instructed to return two weeks later for a secondary suture. He reported six weeks later however, refused the contemplated operation, and demanded the removal of the splint. Examination revealed a soundly healed tendon and within ten days excellent function was restored. This is not an isolated experience with extensor tendons.

## THE PROBLEM OF FLEXOR TENDON INJURIES

Tendon surgery differs from other types of reconstructive procedures in one important respect. Not only must the suture line heal soundly to withstand the tension produced by the contracting muscle, but the line of union must be so smooth that there is no interference with the gliding mechanism.

The repair of an inguinal hernia is frequently followed by impairment of the shutter mechanism of the internal ring, an incident resulting from adhesions occurring between the aponeurosis of the external oblique and conjoint tendon but not necessarily vitiating the result. The inevitable anchorage of the rectus abdominis muscle to its sheath, following a paramedian or rectus splitting incision does not inhibit interfere with the function physiology of the abdominal wall. On the other hand it is conceivable that the scar tissue formation adds to the strength of the abdominal wall or secures the lasting repair of the hernia. In tendon surgery however, the formation of such fibrous tissue or adhesions is detrimental to the result in that union between tendon and sheath ensues, thus preventing or restricting tendon motion.

## TENDON REPAIR WITHIN THE FLEXOR TUNNELS

The outcome of tendon suture is dependent upon several factors. The time interval between the accident and the repair, the degree of contamination at the time of injury, the degree of trauma and tissue loss, and the surgical technique employed, all influence the result. Perhaps the most important consideration upon which the degree of functional recovery can be predicted, is the location of the injury. Severance of flexor tendons in the proximal segment of the finger or the distal inch of the palm generally results in minimal return of function. This critical zone is aptly referred to as "no man's land" by Bunnell (1948), and the reason for the poor return of function following suture in this region is the result of the complex ~~due to~~ the anatomy of the flexor mechanism in the finger. The flexor digitorum profundus and sublimus tendons together with their synovial sheath, are enclosed within a closely-fitting fibro-osseous tunnel, in the region overlying the proximal phalanx. Trauma, however minimal, results in adhesions, which impair the efficiency of the gliding mechanism.

It is not difficult to suture tendons and secure sound union, the real problem is to obtain a ~~freel~~y gliding tendon capable of restoring good function. In the past, attempts to solve the problem, have been made from three directions:-

(1) The perfection of surgical technique in the primary repair. In this respect the greatest amount of clinical effort has been directed towards the refinement of a delicate atraumatic, aseptic, haemostatic technique in the repair of tendons. Notable contributors in this field are Bunnell, Mayer, Koch, Mason and Posch.

(2) The use of reconstructive methods in secondary procedures in an attempt to overcome the poor results of the primary repair. Mayer and Ranshoff (1934), were the pioneers in this field. They attempted to construct a new, non-adherent sheath in order to achieve greater function in tendon grafting, and actually succeeded in doing so. Despite these efforts, free tendon grafts were not

uniformly successful, and good functional results were secured only in the best hands.

(3) The use of membranes, organic and inorganic in the form of tubes or wrappings around the repaired tendon, with the object of reconstructing tendon sheaths and preventing adhesions has been advocated by a host of workers, with conflicting results.

It is with this last approach that this paper is primarily concerned - the experimental production of tendon sheaths using venous grafts.

THE REASONS FOR USING A VENOUS GRAFT

The use of a venous graft as a possible substitute for a damaged tendon sheath, was considered ideal owing to the fact that both tissues have certain properties in common:-

✓ (1) The intima of a vein consists of a layer of endothelial cells not unlike the synovial cells of a tendon sheath, and having a smooth highly polished surface. A smooth surface reduces friction, and is highly conducive to the free gliding of tendons.

(2) Tendons on cross section are circular or oval in shape. A segment of vein has a similar configuration.

(3) On account of its elastic content, a vein is distensible, and could adapt itself accurately to the shape of a tendon without exerting circumferential tension. During healing of a sutured tendon swelling at the suture line is inevitable, owing to the reactionary oedema. A rigid structure placed around a sutured tendon, might therefore, impair the reparative processes, and lead to a delay in the healing of the suture line (Refer to metal and polyethylene tubes - Chapter 3). Should the vein adhere to the tendon and suture line, the elasticity of the vein might allow a certain amount of tendon motion.

(4) Stripped of its adventitia, the wall of a vein is thin,

and corresponds closely to the thickness of a tendon sheath. Furthermore, the thinner the transplant, the better the chances of successful survival.

(5) Segments of vein are readily obtainable in sufficient quantities from suitable subcutaneous veins. The technique for their removal is simple and the loss of such a vein would not cause the patient any ill effects. The use of tunica vaginalis as advocated by Wilmoth (1949) page 44 requires a somewhat involved technique and has definite disadvantages. Furthermore, the ease with which segments of vein grafts are available obviates the necessity to draw on tissue banks.

Autologous transplants have a better prospect of survival than homotransplants in that the tissue is alive at the time of transplantation and infection can be controlled. Long term survival of homotransplants is unusual, and unless they become rapidly vascularised, will subsequently undergo destruction. Even if the homotransplant acquires a blood supply, its survival is still not assured. Weeks after an apparently successful "take" destruction of the transplant may occur, due to the acquisition by the host of an "actively acquired immunity", a phenomenon explained on a theory propounded by Medawar (1944).

Although essentially an experimental thesis, this paper would not be complete without reference to certain fundamental anatomical and physiological considerations, and the healing processes in tendons. Functional anatomy has been stressed over topographical anatomy and purposeful repetition for emphasis has been made where the subject applies in different chapters.

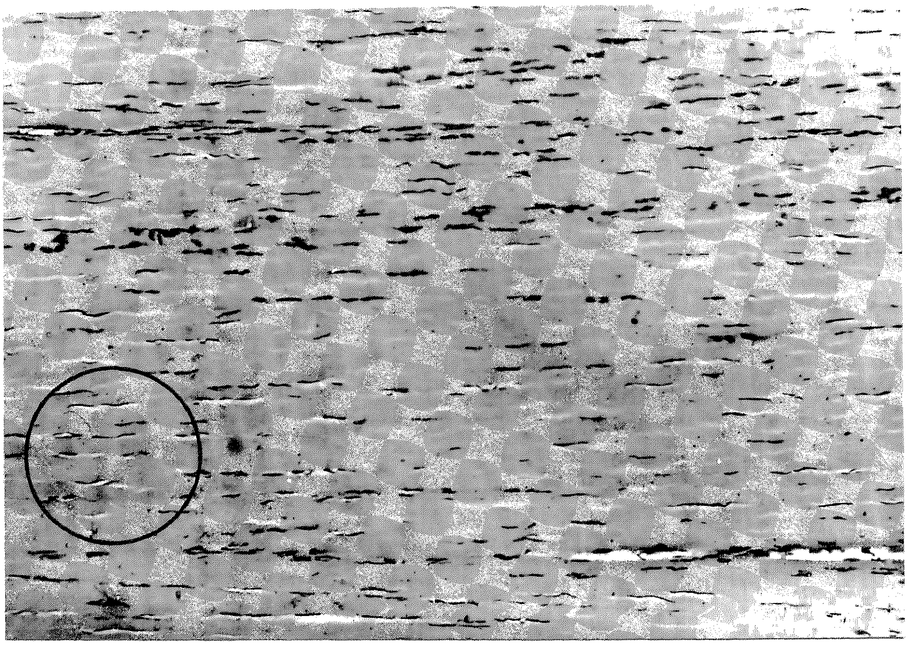


Fig. 3 Photomicrograph of a longitudinal section of tendon (palmaris longus). Human adult. Haematoxylin and Eosin X 140

Note 1. The closely packed thick collagenous fibres fusing with one another at very acute angles, a feature most obvious within the circular area.

2. The darkly stained fibrocyctes arranged in long parallel rows in the spaces between the collagenous fibres.

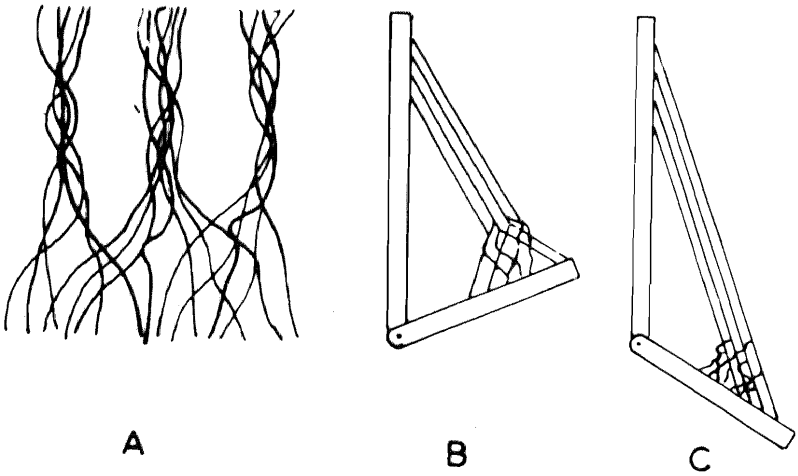


Fig. 4 The fibres of a tendon are plaited (A). This accounts for the difficulty encountered in splitting the fibres of a tendon longitudinally. In different positions of a joint (B) and (C), different fibres take the strain. (After Mollier, reproduced from Grant 1948).

# CHAPTER 2

# THE NORMAL TENDON

## (A) ANATOMICAL AND PHYSIOLOGICAL CONSIDERATIONS

The purpose of this chapter is not to emphasize the gross topography of tendons, a subject well described in most text-books of anatomy, but to discuss the finer anatomical structures of practical significance, and in particular the dynamics of tendon action, a clear conception of which is so essential to the understanding of the problem of tendon injuries and their treatment.

## THE STRUCTURE OF TENDONS

Macroscopically a tendon has a distinct fibrous structure and a characteristic, shining white appearance.

Histologically (Fig. 3), the chief constituents of a tendon consist of thick, closely packed, parallel collagenous bundles, whose structure is similar to that found in loose connective tissue elsewhere. The fibres display a distinct longitudinal striation, and in many places fuse with one another at very acute angles. According to Grant (1948), the fibres of a tendon are not strictly parallel, but plaited, and twine about each other in such a manner that fibres from any given point at the fleshy end of the tendon are represented at all points at the insertional end. Hence, the pull of the whole muscle can be transmitted to any point of the insertion (Fig. 4). In cross section the tendon fibres appear as finely dotted areas usually separated one from another by broken, angular lines, although often continuing into one another. Very fine elastic networks have been described between the collagenous bundles. The fibrocytes are the only cells present, and are arranged in long, parallel rows in the spaces between the collagenous fibres. Their cell bodies are rectangular, or trapezoid, when seen from their surface, and rod-shaped, when seen in profile. The

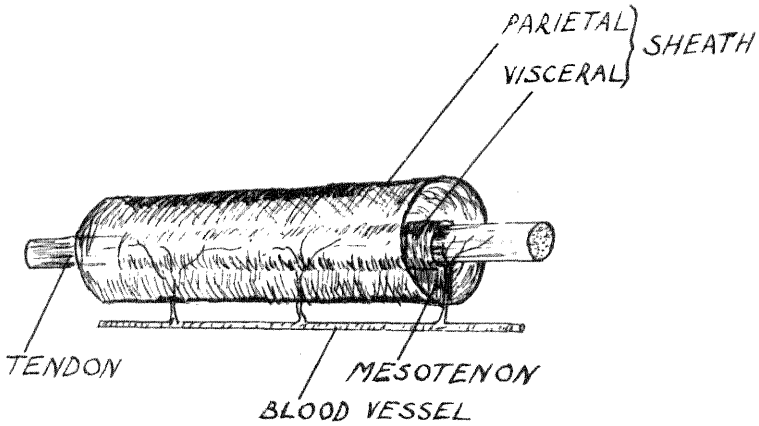


Fig. 5 Diagrammatic representation of the blood supply of a Tendon in Sheath formation After Grant (1948).

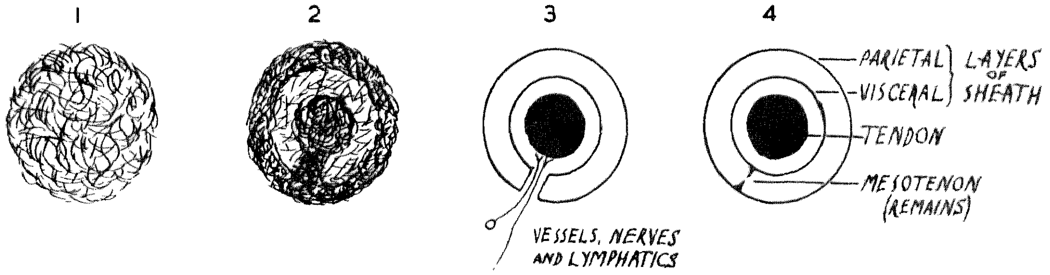
Note that a tendon sheath, consists of two layers - a parietal and a visceral, connected together by the mesotenon. The mesotenon conveys the blood vessels, nerves and lymphatics to the tendon.

cytoplasm of the cell stains darkly with basic dyes and contains a clear attraction sphere adjacent to its round nucleus. Although the limits between the contiguous cells in a row are distinct, the lateral limits of the cell are indistinct because here the cytoplasm continues into a very thin membrane. Occasionally, it can be followed in the transverse direction to another cell row. In a cross section of a tendon, the cells appear as dark, star shaped figures between the collagenous bundles. The whole tendon is comprised of a varying number of small tendon bundles bound together by loose connective tissue, the endotenon, in much the same way as the myoblasts are bound together by their perimysium.

## BLOOD SUPPLY OF TENDONS

Although poorly vascularised, a tendon receives its blood supply from three sources. (1) The muscle proximally, (2) the periosteal insertion distally, (3) the tissues surrounding it along its course, namely, the paratenon, or in the case of tendons invested with a sheath, the mesotenon or vinculae. It is not unreasonable to assume that the synovial fluid of a tendon sheath, similar to that of a joint, contributes to the nourishment of the tendon.

In tendons which are not invested with a synovial sheath, the specialised covering of paratenon is well vascularised, and from this tissue numerous blood vessels enter the substance of the tendon. Tendons in paratenon heal rapidly and are relatively resistant to infection. In the case of tendons invested with a synovial sheath however, the blood vessels travel in the mesotenon (Fig. 5) and enter at the hilus of the tendon. The mesotenon is always situated on that aspect of the tendon least subject to friction. (Fig. 13). Where the mesotenon is deficient, the vessels approach the tendon through the vinculae. On reaching the surface of the tendon, the blood vessels give rise to a



*STAGES IN THE DEVELOPEMENT of TENDON, SYNOVIAL SHEATH AND MESOTENON*

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Fig. 6 Diagrammatic representation of the Stages in the development of Tendon, Synovial Sheath and Mesotenon After Grant (1948).

(1) Represents a mass of undifferentiated mesoderm. The central and peripheral portions of the mesodermal mass (2) by a process of condensation and differentiation give rise to the tendon and sheath respectively. The intervening tissue is the precusor of the sheath space, and develops in much the same manner as a bursa, by a progressive oedema and splitting of the embryonic tissue of the region concerned. A connection between the peripheral and central portions is always maintained, either in whole or in part. This connection is the mesotenon, which conveys the important blood vessels, nerves and lymphatics to the tendon (3). The mesotenon is not always complete, but its remnants will always be found in the form of vinculae. Note that the sheath is a tube within a tube (4). The two component parts, namely the parietal and visceral layers are sealed at either end. Tendons in paratenon are developed in much the same way, except that the cleavage plane between the central and peripheral portions of mesoderm does not occur.

longitudinal vessel which runs in the epitenon and sends out numerous transverse branches which finally enter the tendon. On the whole, the blood supply of tendons in sheaths is meagre, and should the mesotenon suffer injury or destruction, the tendon rapidly succumbs to infection, and reparative processes are seriously retarded or suppressed. Even under ideal conditions, tendons in sheath formation heal slowly and their repair should be undertaken only where asepsis is assured. Serial examination of histological sections of tendons in sheath formation in the monkey revealed few blood vessels, while capillaries were frequently noted in tendons invested with paratenon.

## SENSORY NERVE ENDINGS IN TENDON

The sensory nerve endings of a tendon are located on the surface of the tendon, or at the musculo-tendinous junction (Maximow and Bloom 1944). They are of two types, simple or encapsulated, and are similar to the sensory nerve endings found in striated muscle. In the simple forms, the naked nerve fibres and their branches spread over the surface of the tendon ending in small tree-like forms of different patterns. The encapsulated or composite types, similar to the neuro-muscular spindles, are long and narrow and are situated mainly at the junction of the muscle with tendon.

The physiological significance of the sensory apparatus of tendons is probably the reception of various peripheral stimuli, resulting in sensations of pain, pressure and particularly tendon tension.

## EMBRYOLOGY

A lengthy discourse on the development of tendons is neither of interest nor of practical significance in this study. It would suffice to state that tendons are derived from mesoderm in much the same way as myoblasts, only that they contain no myoplasm (Keith 1948). Fig. 6 represents a diagrammatic illustration of the developing tendon and its sheath.

## THE REGULATION OF TENDON GROWTH

It is essential that the growth of bones, tendons, bl. vessels, and skin, should progress at the same rate to maintain physiological equilibrium, and the mechanism by which this is achieved is highly speculative. Haines (1932) is of the opinion that the bones serve as the pacemakers in the growing limb.

## THE FUNCTION OF A TENDON

The fundamental purpose of a tendon is to transmit the motivating power of a muscle to the site of its action. But not all muscles are endowed with this transmission apparatus. Why is it then, that nature has favoured the incorporation of tendon into some muscles, and not into others? The following physiological considerations must be taken into account to explain the presence of tendons.

### 1. THE CONCENTRATION OF FORCES

The cross-sectional area of the tendon of a muscle has been reduced to much less than that of its corresponding fleshy belly. Therefore the site of insertion of the tendon is precise, and the force of the muscle pull concentrated and focussed. This accounts for the presence of ridges, tubercles, facets and traction epiphyses. If the insertion were fleshy, the attachment would be diffuse and the forces dissipated.

### 2. ELIMINATION OF PRESSURE EFFECT

Muscle is a fleshy tissue, vascular and too highly specialised to withstand pressure. Consequently, whenever a muscle is subjected to pressure and friction, as will occur when it plays or rubs up against a bone or ligament, its fleshy fibres are replaced by tendon composed of unspecialised tissue of great strength and flexibility and designed to withstand pressure. Common examples of this transformation are seen predominantly in the hand and foot, where the long muscle bellies cross the bony prominences or retinaculae; the shoulder joint, where the long head of the biceps passes over the head of the humerus and down the bicipital groove; and in the orbit where the rectus superior obliquus muscle curves around the trochlea. The digastric and omohyoid muscles are similarly replaced by tendons where subject to pressure.

Tendons are also present upon adjacent surfaces of muscles whenever much gliding of muscle upon muscle takes place. This condition is well seen in the case of the vastus externus and soleus. Occasionally the presence of tendons in certain situations does not serve any obvious purpose, and can only be explained on the basis of phylogenetic senility. Wood Jones (1944) states that "tendons representing as they do a lower stage of organisation, than the more highly specialised muscle substances, may be developed merely as a degeneration product of muscles which are waning in importance." The proportion of tendon to contractile tissue in the palmaris longus far exceeds the ratio of any of the forearm muscles. This muscle belongs to a primitive group of superficial flexors that originally acted on the proximal phalanges. The function of the palmaris longus has been superseded by lumbricals with the consequent phylogenetic reduction of the former. In the leg, an analagous situation exists in the plantaris muscle, the tendinous portion being five times longer than the muscle belly.

Unless some mechanical reason demands the presence of a tendon, muscles that have a large proportion of tendon in their composition should be regarded as having passed into phylogenetic senility.

### 3. THE CONSERVATION OF SPACE

Tendons are developed wherever the "packing" of structures is necessary. The presence of muscle tissue in the fingers

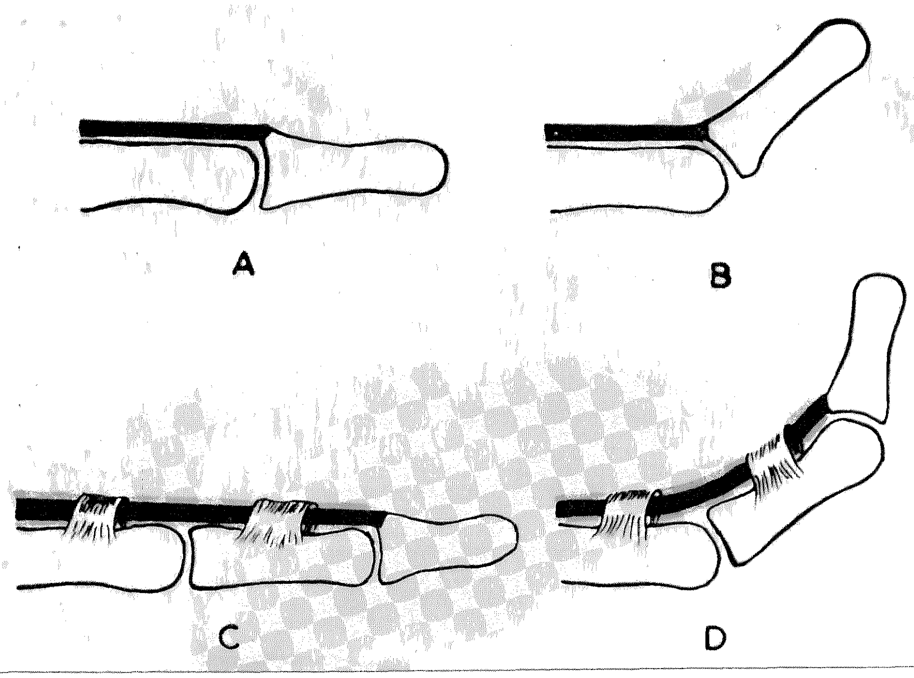


Fig. 7 The gliding mechanism of a tendon depends upon its direction of motion.

A and B represent the action of the extensor digitorum communis tendon on the metacarpo-phalangeal joint. Note that the tendon does not pass over the joint, and that it pursues a straight course, whether the joint is in the neutral (A) or extended position (B). Tendons acting in this manner will be invested with paratenon. On flexion of the joint however, (not illustrated), the terminal portion of the tendon will change its direction to conform to the curve of metacarpal head, and it should therefore be invested with a sheath. In actual fact it is, the joint capsule acting as a modified tendon sheath.
C and D represent the action of the flexor digitorum profundus tendon on the terminal phalanx of the finger. Note that the tendon passes over joints, and that when the digit is flexed, the tendon changes its direction of motion and becomes angulated. Tendons behaving in this manner will be invested with a tendon sheath and must of necessity have restraining bands (annular ligaments or pulleys), to prevent bowstringing.

would alter their shape and form on contracting, a factor incompatible with the delicate function required of the hand.

To prevent bowstringing of tendons, when a change of direction of a tendon occurs, fibro-osseous tunnels are developed. These tunnels are rigid and inextensible structures through which the snug fitting tendons move to and fro. A muscle on contracting shortens, and must of necessity increase its cross-sectional area. The presence of muscle tissue in these fibro-osseous tunnels on contracting, would produce considerable tension and its motion would be considerably impaired.

## THE TENSILE STRENGTH OF TENDONS

The fibres of a tendon form a flexible tissue which offers great resistance to a pulling force. Nicola (1934) who experimented with four human tendons, reported that their average tensile strength was 7,330 pounds per square inch. Cronkite (1935) determined the tensile strength of 294 human tendons, some fresh, but most from the dissecting room. He found a considerable variation in the results, not only in the different cadavers, but in specimens from the same cadaver. The range for the whole series varied between 4,000 and 30,000 pounds per square inch, while most ranged from 8,700 to 18,000 pounds per square inch. There was no difference in the tensile strength of fresh specimens as compared to those tested in the cadaver.

## THE ANATOMY OF THE GLIDING MECHANISM.

The gliding mechanism of a tendon, depends upon the direction of its motion. Where a tendon pursues a straight course, gliding is facilitated by an investment of specialised fatty elastic tissue, known as paratenon. Should the tendon at some phase of its motion change its direction, the gliding mechanism is dependent upon the presence of a tendon sheath.

As a general rule, tendons will have synovial sheaths wherever they pass over joints to act on more distal joints.

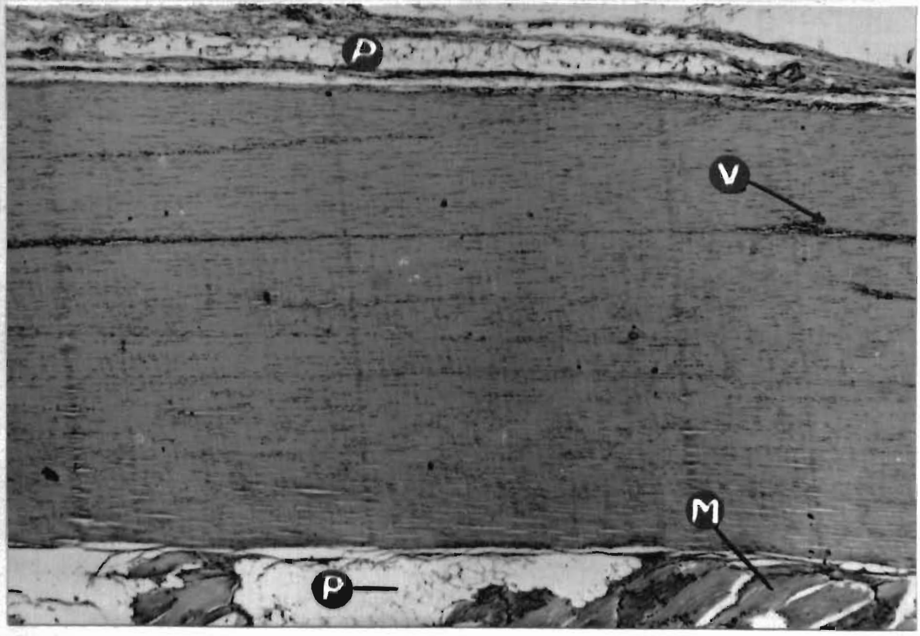


Fig. 8 Photomicrograph of tendon in paratenon. (Human).
Haematoxylin and Eosin X 45

Note the paratenon (P) surrounding the tendon, and containing fat cells identifiable as clear spaces bounded by cell membranes of mosaic appearance.

(M) Musculotendinous junction.
(V) Blood vessel.

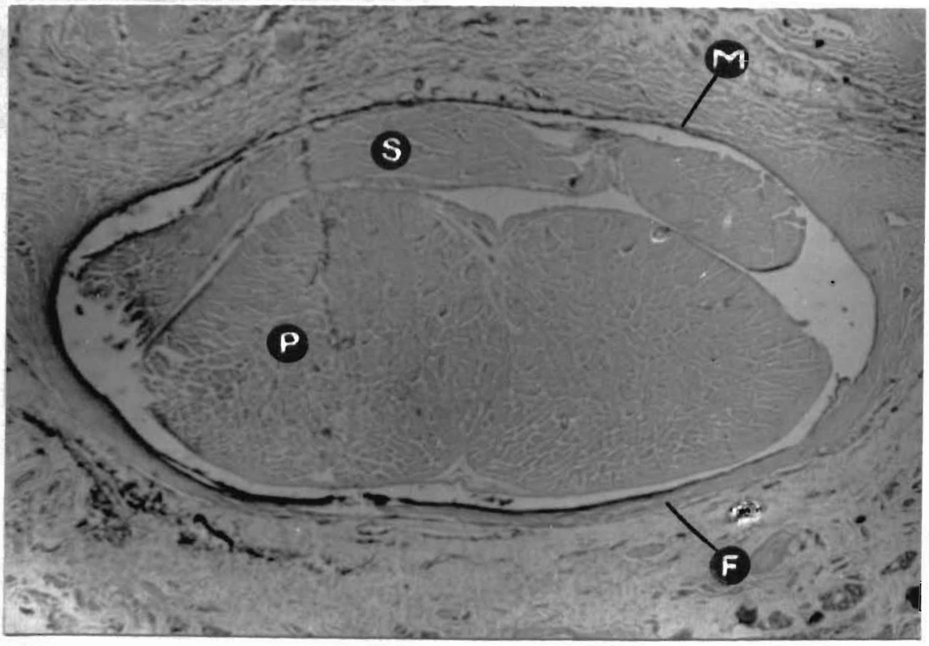


Fig. 9 Photomicrograph of a tendon in sheath formation. (C. Aethiops).
Haematoxylin and Eosin X 30

A transverse section through the digital sheath opposite the distal half of the proximal phalanx. Note the well circumscribed sheath.

(S) Tendon of flexor digitorum sublimus.
(P) Tendon of flexor digitorum profundus.
(M) Parietal layer of tendon sheath.
(F) Fibrous layer of tendon sheath.

However, where they merely straighten joints back from a bent position without crossing joints, they will not be invested with a sheath (Fig. 7). In the hand we will therefore find sheaths enveloping the flexor and extensor tendons at the wrist and the flexor tendons of the fingers, but not the extensors on the back of the hand nor on the back of the fingers.

## THE GLIDING OF TENDONS IN PARATENON

Tendons which are not surrounded by a sheath are invested with paratenon, a fatty elastic areolar tissue, which is vascular and rich in blood supply (Fig. 8). The paratenon completely fills the interstices of the fascial compartment in which the tendon lies and it blends with the perimysium, the perineurium, and the adventitia of the neighbouring blood vessels. Its elasticity enables it to stretch several centimetres, and this feature is of paramount importance in that it allows unrestricted gliding of the tendon. The long elastic fibres of the paratenon running between the overlying fascia and tendon are coiled and tortuous at rest. When motion occurs in either direction, the elastic fibres straighten out. The tendon therefore in reality, does not glide through the paratenon, but on account of its attachment to the overlying fascia merely drags this loose connective tissue with it in one or other direction. Thus the paratenon immediately investing the tendon moves with the tendon, whereas the peripheral portion which is attached to the overlying fascia remains immobile.

Paratenon formation is seen on the volar and dorsal aspects of the distal part of the forearm, proximal to the tendon sheaths, and over the dorsum of the hand and foot. It is present in abundance in the palm where it extends between the ulnar bursa and the sheaths of the index, middle and ring fingers.

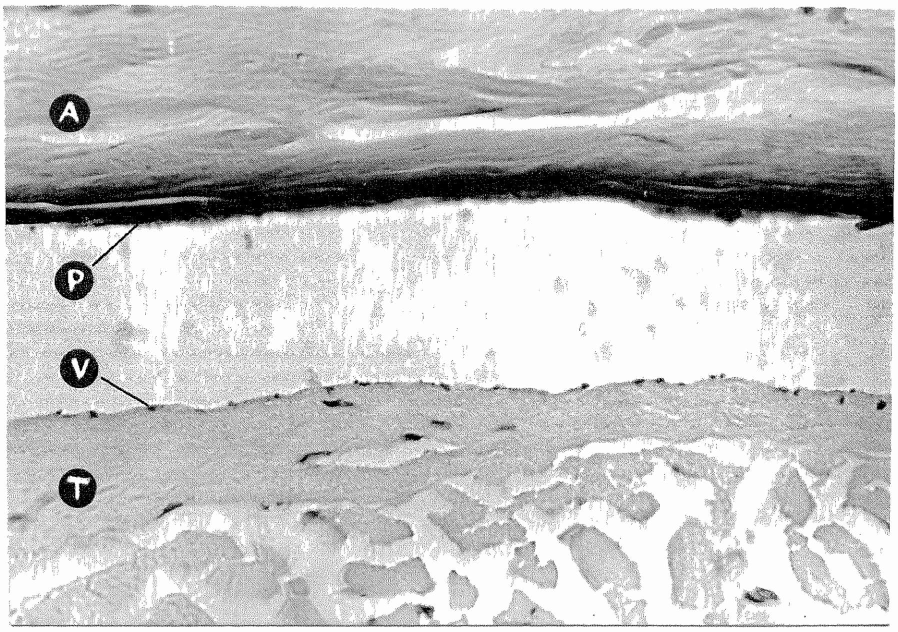


**Fig. 10** Photomicrograph of a tendon in sheath formation to show the visceral endothelial layer.
(C. Aethiops).

Haematoxylin and Eosin X 700

A transverse section through the digital flexor sheath at the level of the middle of the proximal phalanx.

(A) The annular ligament. Note the coarse wavy collagenous fibres.
(P) The parietal layer of the synovial sheath.
(V) The visceral layer of the synovial sheath. Note that it consists of a single layer of flattened endothelium. Epitenon is not conspicuous in this region, the friction bearing surface of the tendon.
(T) Tendon (flexor digitorum profundus).

## TENDONS IN SHEATH FORMATION

Correctly conceived, a tendon sheath corresponds to a joint in that it is a sharply circumscribed cavity (Fig. 9), containing a lubricating fluid not unlike the synovial fluid of joints. Histologically, the wall of a tendon sheath is composed of a layer of synovial cells, corresponding to the synovial layer of a joint (Figs. 10 and 14). The function of the sheath is to act as a fluid buffer whenever a tendon is subjected to friction or pressure, on two or more surfaces. It does not however allow the tendon an increased range of movement, since the excursion proximal to the sheath is the same as that within it. Tendon sheaths are seen predominantly in the hand (Fig. 11) and foot, and in all instances the friction results from the presence of bone on one surface, or a retinacular ligament on the other.

Occasionally, when a tendon changes its direction it is not invested with a sheath, as instanced in the case of the quadriceps and patella tendons. Here, the knee joint takes the place of the sheath. A similar arrangement exists where the extensor digitorum longus tendon crosses the metacarpo-phalangeal joint, the tendon substituting for the posterior ligament of that joint.

A tendon sheath may be compared to a bursa and differs only in the degree of development. In fact it consists of two layers, a visceral and a parietal enclosing a potential cavity sealed at both ends. A bursa on the other hand, protects a relatively small portion of a tendon. Many tendon sheaths however, fall far short of completely enclosing tendons, for example, that of the peroneus tertius; whereas some sheaths such as that associated with the flexor carpi radialis longus, envelope more than half of the circumference of the tendon. Full development of tendon sheaths is found in the digits where the long flexor tendons are completely enveloped.

Fig. 11 The disposition of the tendon sheaths on the volar aspect of the hand

In the palm, wrist and distal forearm, the long flexor tendons to the index, middle, ring and little fingers are invested with a common sheath - the ulnar bursa. Between the digital sheaths of these fingers and the ulnar bursa, the flexor tendons are invested with paratenon, because in the palm, these tendons do not angulate but pursue a straight course.

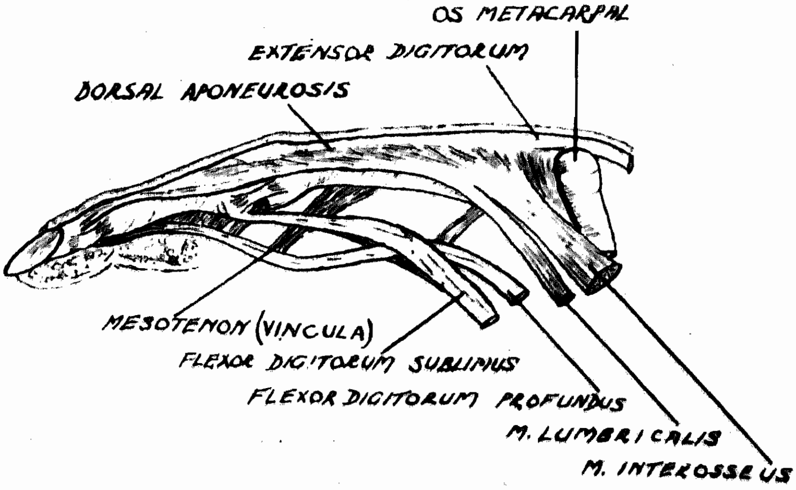


Fig. 12 The Vinculae.

The mesotenon when deficient is represented by narrow membranes, the vinculae.

Fig. 13 Photomicrograph of tendon in sheath formation to show the mesotenon. (C. Aethiops).
Haematoxylin and Eosin X 30

A longitudinal section of the flexor digitorum profundus tendon in the digital sheath, at the level of the distal half of the middle phalanx. The tendon of the flexor digitorum sublimus is not visible in this section, having already inserted into the proximal portion of the middle phalanx.

(P) The middle phalanx. Note the osteoblasts in the cortex.

(M) The mesotenon, which is attached to the hilus of the tendon away from the friction bearing surface of the tendon.

(S) The sheath space, which is clearly defined and normally contains synovial fluid.

(F) The fibrous sheath, lined on the inner aspect by the parietal layer of the synovial sheath. Note the thickening of the fibrous sheath (on the left hand side of the photomicrograph), due to the presence of the annular ligament.

## THE MESOTENON

On opening a tendon sheath and retracting the tendon from its bed, a delicate connective tissue membrane is seen connecting the tendon with the floor of the sheath. This structure, the mesotenon, is analogous to the mesentry of the intestine, and its function is to convey blood vessels, lymphatics and nerves to the tendon. Its insertion into the tendon, called the hilus, is always situated on the longitudinally convex surface of the tendon which is least exposed to friction (Fig. 13). The connective tissue of the mesotenon completely envelopes the tendon to form the epitenon (Fig. 14) and it sends numerous septa, endotenon into the depths of the tendon, thus separating the tendon into bundles. On allowing the retracted tendon to fall back into the sheath, the mesotenon forms numerous folds to adapt itself to the narrow confines of the sheath. The mesotenon is not always present. It may be absent or present in part, thus differing from the mesentry which is usually intact. According to Mayer (1916) the mesotenon is absent from the tendons of flexor digitorum profundus in 50% of cases. In the digital sheaths of the Monkeys used in this study, the mesotenon was usually found to be intact. When partially present, it is represented at each end of the sheath by a short membrane - the vinculum triangulare or vinculum quadrangulare (Fig. 12), the name designated depending on its shape. When reduced to a very minimum, the residual mesotena are usually present in the form of one or more fine strands - the vinculae filiformia. The mesotenon or its remnants, like the paratenon is an extensible structure so loose and filmy, that it does not hinder tendon motion. As the mesotenon approaches the insertion of the tendon its width diminishes. The width of the mesotenon between the bone and tendon indicates the amplitude of tendon excursion, the wider the mesotenon the greater the extent of motion.

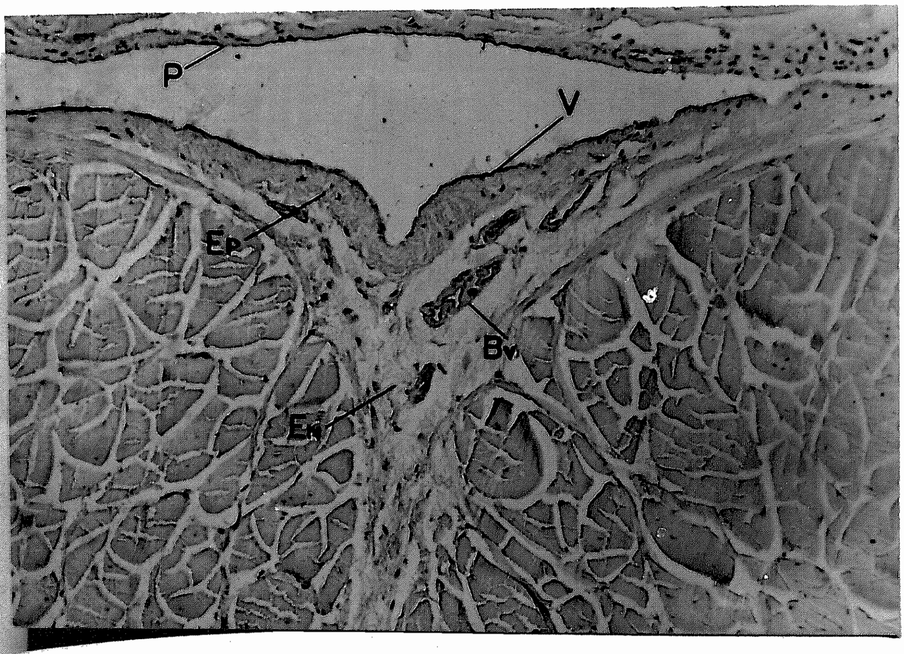


Fig. 14 Photomicrograph of a transverse section of tendon in sheath formation showing the epitenon and endotenon. (C. Aethiops).
Haematoxylin and Eosin X 150

This section was taken at the level of the distal half of the proximal phalanx of the index finger.

| | |
|---|---|
| (Ep) | The epitenon, a connective tissue layer which completely envelopes the tendon. |
| (En) | The endotenon, derived from the epitenon, penetrating the substance of the tendon, and separating the tendon into bundles. |
| (Bv) | A blood vessel in the epitenon. |
| (P) | The parietal layer of synovial sheath. |
| (V) | The visceral layer of synovial sheath. |

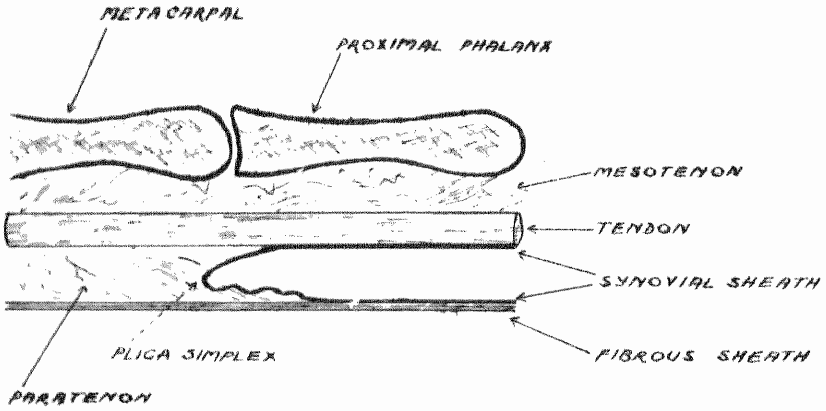


Fig. 15 Diagrammatic representation of the mode of entry of a tendon into its sheath, and the plica simplex. Modified from Mayer (1916,1952).

This illustration represents a longitudinal section through the proximal pole of the digital sheath. The pouch at the proximal part of the sheath does not lie between the tendon and the fibrous fascia, but between the paratenon covering the tendon, and the fascia. The tendon therefore, on entering the sheath is not suddenly divested of its loose connective tissue envelope, but is accompanied by the paratenon for a variable distance to form the plica simplex. The plica consists of a very loose vascular connective tissue lined by a layer of cells continuous with the synovial lining of the sheath. (The flexor digitorum sublimus tendon has been deliberately omitted from this diagram for clarity.)

## THE DYNAMICS OF TENDON GLIDING

Mayer (1916) compared the gliding of a tendon within its sheath, to the motion of a piston within a cylinder. The analogy, however, is not accurate, for in the latter there is no attachment between the piston and cylinder, whereas in the former, the tendon is attached at either end to the fibrous covering through the intermediary of the synovial sheath. One would expect that this attachment would hamper and restrict the movement of the tendon. On the contrary, through the medium of an ingenious mechanical device at the proximal pole of the tendon, the plica, the sheath though closely united on the one hand to the immovable overlying fascia, and on the other hand to the freely gliding tendon, can without restriction, accompany every motion of the tendon. For an understanding of the mechanism of gliding, a knowledge of the method of entry of a tendon into its sheath is most essential.

## THE MODE OF ENTRY OF A TENDON INTO ITS SHEATH

Hartman (quoted by Mayer, 1916) was the first to draw attention to the fact that a tendon on entering its sheath is not suddenly divested of its surrounding connective tissue, but is invested with a loose envelope of paratenon continuing for some distance within the sheath, simulating the reflection of the conjunctiva of the lid onto the bulb. This reflection or fold is known as the plica (Fig. 15) and it serves to facilitate motion of the tendon without interrupting the continuity of the synovial membrane of the sheath. In some sheaths, this connective tissue envelope is more complex than in others and is doubled on itself to form a tongue like projection, the plica duplicata (Fig. 16), thus transforming the proximal pole of the sheath into two compartments - a superficial, and a deep. The presence of a plica duplicata merely indicates that the tendon has a greater amplitude of excursion. During contraction of the

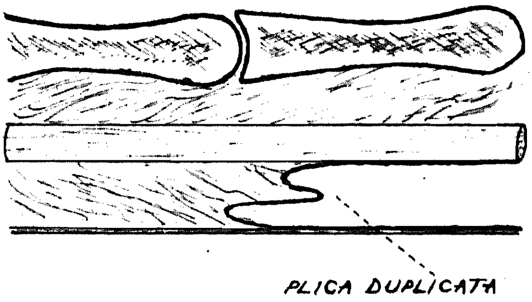


Fig. 16 Diagrammatic representation of the plica duplicata

The plica duplicata is simply a duplication of the plica simplex, which forms a tongue-like projection into the sheath and dividing the proximal portion of the sheath into two compartments; a superficial and a deep. The plica duplicata is not a constant feature in all tendon sheaths. Its presence however, indicates that the tendon has a wide range of motion. In this illustration, the tendon is at rest. Note that the elastic fibres of the paratenon and mesotenon are tortuous. Compare with Fig. 17.

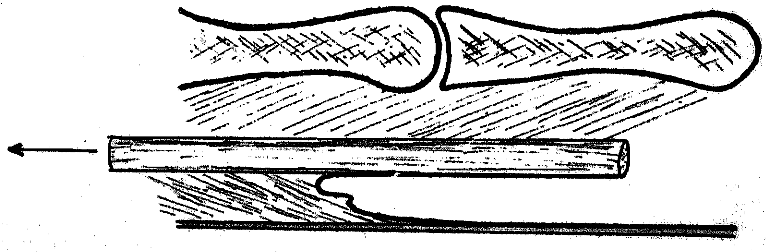


Fig. 17 Diagrammatic representation of the Mechanism of Gliding.

The muscle has contracted, and the tendon has moved in the direction indicated by the arrow. In order to permit the unrestricted motion of the tendon, the deep pocket of the plica duplicata (Fig. 16) has taken up the loose prepuce or fold of synovium to form a single pocket. Note that the elastic fibres of the paratenon and mesotenon coiled in Figs. 15 and 16 are now straight.

muscle, invagination of the plica occurs, the deep pocket becomes longer and the superficial pocket becomes shallower. (Fig. 17). Reference to Figs. 15, 16, and 17, will simplify the understanding of the method of entry of a tendon into the sheath and the mechanism of gliding.

## THE MECHANISM OF GLIDING

In Fig. 16 the tendon is at rest. In Fig. 17 the muscle has contracted and to permit the unrestricted motion of the tendon, the deep pocket takes up the loose fold of synovium and ultimately forms a single pocket. Note that the fibrous sheath has remained stationery. The proximal part of the sheath however, although attached to the immobile fascia, has, by virtue of the elasticity of the paratenon followed the motion of the tendon. Note also, that the elastic fibres of the paratenon coiled at rest, are now straightened. This type of invagination is not constant. In some instances motion occurs mainly by a deepening of the pocket between the plica and the tendon, the slack in the paratenon is taken up, with little or no change in the form of the plica.

Proximal to the sheath in the palm, the gliding of the tendon beneath the comparatively rigid fascia, is permitted by the elasticity of the paratenon. Tendon sheaths are not found in the palm, neither are they necessary, for in this situation the tendons pursue a straight course.

## TENDON TENSION

The tension in a tendon which has been sutured is of great practical significance, for the outcome of a tendon suture will depend apart from other factors on whether the tendon is sutured under maximal, zero, or negative tension.

Mayer (1916), as a result of experiments on dogs, and by control observations during the course of operations on human beings, determined the tension of tendons when their muscles were at rest and the individual under deep anaesthesia. This was an important practical consideration, for the surgeon who wishes to suture a tendon physiologically must suture the tendon under this tension.

In Mayer's experiments in dogs, a tendon, generally the tibialis anticus or the Achilles tendon was exposed 2 cm. proximal to its insertion. The tendon was securely braided by an overlapping suture in such a way as to allow great traction to be exerted upon the suture without it tearing out of the tendon. The tendon was then divided just distal to the insertion of the suture, and the free end of the suture attached to a delicate spiral scale. The tension of the tendon was accurately recorded by simply moving the handle of the scale until the divided ends were brought into apposition. The results of these measurements showed that when the origin and insertion of a muscle and its tendon were approximated, and the muscle made to contract by faradic stimulation the tendon under the condition of the experiment (deep narcosis) was entirely without tension. In the case of the Achilles tendon, if the dog's knee was flexed and at the same time the foot was brought into a position of equinus, the tendon ends actually overlapped, i.e., the tendon was under <u>negative</u> tension. "Conversely, when the knee was extended and the foot brought into the position of calcaneus, it was absolutel impossible, even with a traction of 30 pounds to bring the tendon stumps together; the muscle and tendon were evidently being taxed beyond their normal physiological length." Muscle and tendon have a definite length, termed the physiological length. This length can vary within the range of the normal motion of the joints bridged by the muscle and tendon. If an abnormal position of the joints is assumed as for instance, in the case of the dog, extreme flexion of the knee and hyperextension of the foot, tendon and muscle are unable to accommodate themselves to this unusual demand.

Certain aspects of Mayer's experiments were repeated by the author, and the results noted confirmed his observations.

Under deep Nembutal anaesthesia the tendo Achilles of the dog was exposed and divided. The knee joint was then flexed and the ankle joint extended: the free ends of the divided tendon overlapped by almost half an inch. The gastrocnemius muscle was then stimulated using a faradic current. Although the extent of tendon overlap decreased, retraction of the divided tendon did not occur even with maximal stimulation.

## THE PRACTICAL APPLICATION OF PHYSIOLOGICAL TENSION

If for example, the action of a particular tendon is one of flexion, the joints upon which the tendon acts should be immobilised in flexion until firm union has occurred. Neglect to observe this physiological tension might result in failure, for the excessive tension on the suture line which will occur if the joints are immobilised in extension will result in disruption of the suture line, or should the suture hold, degeneration of the muscle. In actual practice the joints should not be fully flexed as this will result in over-stretching of joint capsules. Although under these circumstances the tendon tension will not be zero, the minimal tension which will result is actually beneficial in that a certain degree of functional activity is possible, a factor which has considerable influence on the rate of healing of tendons. (See page 33).

Physiological tension has further practical applications in tendon transfers and tendon grafting. In tendon transfers, to restore normal tension, one need only approximate the origin and insertion of the transferred muscle and tendon, and suture the tendon to its new position without any tension. For example, in transplanting the peroneus longus tendon to compensate for paralysis of the tibialis anticus, the foot should be held in the position of calcaneo-varus and the peroneus tendon sutured to its new point of insertion with just sufficient tension to render it taut. In the secondary repair of tendons it is usually necessary to resort to free tendon grafting instead of direct tendon suture, because it is rarely possible to unite the separated ends of the tendon without doing so under too great a tension. Tendon grafts when healing have a tendency to contract, so that to ensure physiological tension, when placing a graft, it should be slightly longer than the tendon defect.

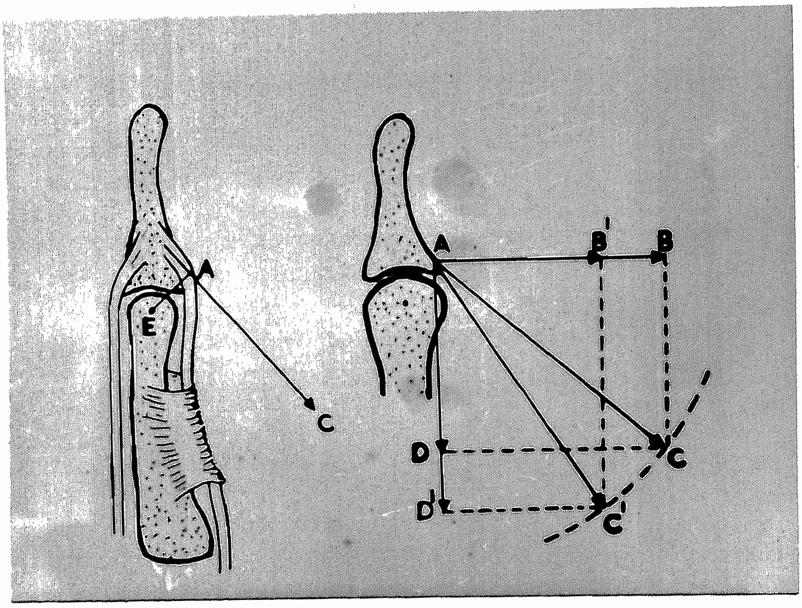
## THE AMPLITUDE OF EXCURSIONS OF TENDONS

To move a joint, the activating tendon must slide a certain distance, the distance known as the amplitude of motion or excursion. The amplitude of excursion varies in different tendons, for the range of movement in different joints is variable. Furthermore, some tendons have a greater range of motion than others in that they activate several joints, whereas others will have a lesser range in that they move only one or two joints. The amplitude of excursion of the tendon of the flexor digitorum profundus muscle, for example, is double that of the tendon of the abductor pollicis longus. (Table I). The former tendon moves four joints (the wrist, metacarpophalangeal, and interphalangeal joints), whereas the latter moves only two joints (the wrist and metacarpophalangeal joint of the thumb).

| | |
|---|---|
| Wrist tendons ........................ | 1.1/4 inches |
| Flexor digitorum profundus .......... | 2.3/4 inches |
| Flexor digitorum sublimus ........... | 2.1/2 inches |
| Flexor pollicis longus .............. | 2.1/16inches |
| Extensor digitorum communis ......... | 2 inches |
| Extensor pollicis longus ............ | 2.1/4 inches |
| Extensor pollicis brevis ............ | 1.1/8 inches |
| Abductor pollicis longus ............ | 1.1/8 inches |

Table I. Average total amplitude of excursion of tendons above the wrist. (Bunnell 1948).

Following the repair of a divided tendon, the amplitude of tendon motion is limited, the degree of limitation depending upon two factors: (a) the length of tendon shortening, which inevitably follows excision of the traumatised stumps and (b) the site, extent and nature of the



(a) (b)

Fig. 18 Diagrammatic illustration of the Mechanics of Motion at the distal interphalangeal joint

(a) Note the expansion of the base of the terminal phalanx, to which the flexor digitorum profundus tendon is attached, and the length of lever arm (AE) between the insertion of the tendon (A) and the centre of motion of the joint (E).

(b) The component forces of tendon action - flexion and stabilisation, are proportional to the sine and cosine of the angle of approach

AC represents the direction of pull of the tendon and CAD or $\alpha$ the angle of approach. Note that the expansion of the head of the middle phalanx enhances the angle of approach.

Now, when the angle of approach of the tendon is CAD, then AB represents the flexional force, and AD represents the stabilising force. If the angle of approach is decreased to C'AD, the magnitude of the flexional force is reduced to AB' while the magnitude of the stabilising force is increased to AD'.

Expressed trigonometrically $\cos.\alpha \quad (\widehat{CAD}) = \frac{AD}{AC}$

and $\sin.\alpha \quad (\widehat{CAD}) = \frac{DC}{AC}$

Therefore AD is proportional to $\cos.\alpha$
and DC is proportional to $\sin.\alpha$
but DC = AB (Flexional force)
Therefore, the stabilising force AD is proportional to $\cos.\alpha$ and the flexional force AB proportional to $\sin.\alpha$

peritendinous adhesions. A tendon which has a limited amplitude of excursion can move its individual joints fairly well but is unable to completely flex all the joints at once. If the tendon has been repaired in the palm or above the wrist normal function is more likely to be restored than in a tendon repaired in the digital sheath. In the palm and above the wrist, the tendons are invested with paratenon, and the adhesions which form in these areas are more capable of mobilisation than the denser adhesions which form in the digital sheath. The limited exçursion of a flexor tendon not only hampers flexion but also restricts extension and vice versa.

A knowledge of tendon excursion is of practical application. In the selection of a tendon for transfer to compensate for the loss of action of another, a tendon having at least the same amplitude of excursion as the normal tendon is essential in order to achieve a good functional result. Furthermore, a tendon should not be transferred to two or more tendons which have a different amplitude of excursion. Thus a transferred tendon should not be attached to both the extensor pollicis longus and the abductor pollicis longus tendons, because the amplitude of the former is twice that of the latter.

## INSERTIONS OF TENDONS AND THE MECHANICS OF JOINT MOTION

To ensure the mechanical efficiency of the interphalangeal joints, the digital tendons are inserted near the proximal ends of the phalanges, close to the axis of movement. This arrangement helps to retain in apposition the ends of the bones constituting the joints, thereby giving them stabilisation. In addition, a rapid movement of the joint is produced at the expense of a relatively small amplitude of tendon excursion. Stabilisation of joints however, is not entirely dependent on the contracting tendons The tension of the opposing tendons, the collateral ligaments

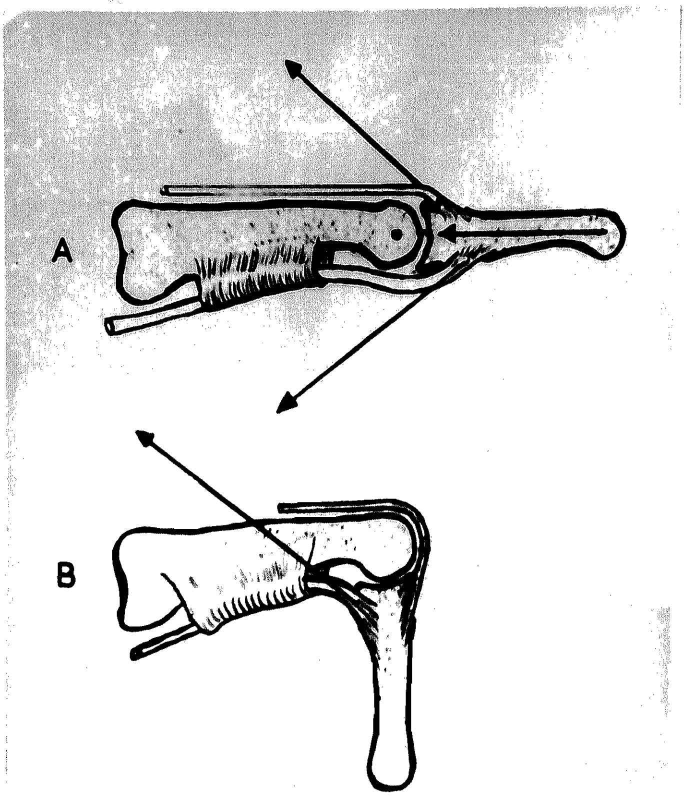


Fig. 19 The role of the Annular Ligaments in regulating the angle of tendon approach

In A the terminal interphalangeal joint is in extension and in B the joint is in flexion. Note, that through the medium of the annular ligament the angle of approach of the flexor digitorum profundus tendon is effectively maintained, whether the joint is in flexion or extension. Compare with Fig. 20.

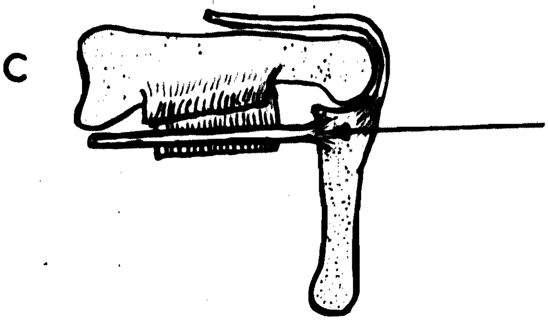


Fig. 20 The effect of destruction of the Annular Ligament

Note the bowstringing of the tendon, and the increase of the angle of approach of the tendon to a right angle when the joint is flexed. The force of tendon action is thus that of flexion and none of stabilisation. Although the force of flexion is increased, the degree of flexion is decreased on account of the relative lengthening of tendon.

and the configuration of the bones constituting the joints contribute to a large extent.

In order that a tendon may effectively move a joint, there must be some length of lever arm between the insertion of the tendon and the centre of motion of the joint. Increased lever action is afforded by the prominent tendon insertions at the base of the phalanges. (Fig. 18a). Despite the relatively short length of lever arm, this method of insertion, although resulting in a small mechanical advantage, confers a greater velocity ratio, thereby producing a rapid movement of the distal end of the phalanx. Should the insertion be towards the distal end of the phalanx, the movement produced would be more powerful, but, it would also be slower.

The degree of flexion of the joint depends upon the angle of approach of the tendon; the greater the angle the more flexion effect the tendon will have. Conversely, the less the angle, the greater the stabilising effect and less the effect on flexion. To increase the angle of approach of tendon to bone, the distal end of each phalanx is expanded, thus giving a wider angle of approach for both flexor and extensor tendons. The component forces of tendon action, that is flexion and stabilisation are proportional to the sine and cosine of the angle of approach as expressed mathematically. (Fig. 18b). As the joint flexes, the angle of approach increases, and the tendon gains in rotary and loses in stabilising effect. Should the angle of approach reach a right angle, the whole action would be one of flexion and none of stabilisation, a situation which would predispose to inefficient joint action. The annular ligaments play a significant part in regulating the angles of approach and thus indirectly help to maintain the stabilisation of the joint as the angle of flexion increases. (Fig. 19). The loop which the flexor digitorum sublimus forms as it straddles

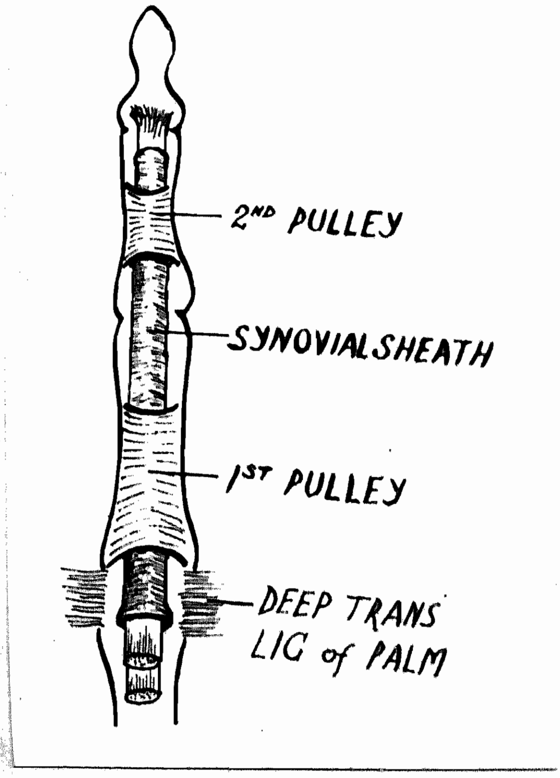


Fig. 21 The digital sheath illustrating the annular ligaments or pulleys

Note the two digital flexor tendons, the flexor digitorum profundus and sublimus entering the digital sheath. The sheath extends from the palmar ligament of the metacarpo-phalangeal joint to near the insertion of the profundus tendon into the base of the distal phalanx. The annular ligaments or pulleys which together with the phalanges constitute the fibro-osseous tunnels restrain the tendons from bowstringing when the finger is in flexion. For functional purposes, the tissues over the joints must be pliable and for this reason, the annular ligaments are deficient over the joints.

the flexor profundus, controls the angle of approach of the latter tendon on the middle phalanx.

The extensor tendons of the fingers have a good angle of approach when the digital joints are in flexion. When the joints approach extension however, the angle of approach lessens and consequently the force of extension diminishes. Annular ligaments are not necessary on the dorsum of the finger for hyperextension does not normally occur at the interphalangeal joints.

## THE ANNULAR LIGAMENTS OR PULLEYS

Reference has already been made to the role of the annular ligaments in regulating the angles of approach of tendons. Furthermore, these ligaments subserve the very important function of preventing the bowing of tendons across the joints on flexion and thus preclude the relative increase in the length of the tendon. In order to completely flex the joints of a finger, the flexor digitorum profundus tendon must make an average excursion of one and three-eighth inches. (Bunnell 1948). Destruction of these ligaments would allow too much slack in the tendon for complete flexion of the joints and the mechanical efficiency of tendon action would consequently be greatly impaired. (Fig. 20). The annular ligaments should, therefore, be treated with the respect they deserve, and must be preserved during reconstructive procedures on tendons or reconstituted when destroyed.

## (B) THE PROCESS OF TENDON HEALING

A knowledge of the process of tendon healing is most essential for the rational treatment of tendon injuries. Various factors such as the period of immobilisation and the effect of functional activity have a considerable influence on the final outcome.

## * HISTORICAL REVIEW OF EXPERIMENTAL STUDIES ON TENDON HEALING

The actual process of tendon repair, apparently first studied by Hunter in 1767 is still the subject of controversy.

According to Hunter, tendons healed by the formation of callus, produced in much the same manner as bone callus. Ammon in 1837, considered that the defect left by tendon injuries was first filled by a formless exudate, and that later the tendon stumps themselves regenerated the new tendon. Bouvier and Velpeau, expressed the opinion that the new tissue owed its origin mainly to the sheath tissues surrounding the tendon. Paget in 1853 observed that the tendon defect was first filled with a fluid exudate which was eventually replaced by fibrous tissue and which gradually took on the appearance of tendon. Pirogoff attached great significance to the fluid exudate and stated that it was a sine qua non in tendon repair, for it not only stimulated the surrounding tissues but furnished some of the material for the new tendon. Without the exudate, an incomplete scar formed with little or no union, whereas in the presence of an exudate the regeneration was good. Dembowski believed that the new tendon was formed by cells that wandered from the blood into the defect. His conclusions were based on the observation that the cells in the new tendon contained a dye that had been previously injected into the blood stream. According to Belzow, the tendon stumps played some part in the new formation of tendon and in the organisation of the scar. The intervening tissue between the stumps, however, was

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* An abstract from Mason and Shearon (1932). The process of tendon repair; an experimental study of tendon suture and tendon graft. Arch. Surg. 25:615.

essentially a scar, since it tended to retract. Despite the marked histologic resemblance to tendon, he considered that the new tissue was not a true tendon regeneration. Viering believed that the peritendinous and intratendinous connective tissues were the main sources of material for the organisation of the tendon scar. Enderlen in 1893 studied the reparative processes in the tendo Achilles of the guinea pig and demonstrated the importance of the tendon cells themselves in the regenerative process. He showed that the healing of the tendon wound was due to proliferative changes on the part of the tendon, the intratendinous and peritendinous tissues, and to some extent on the surrounding connective tissues. He stressed, however, the early and abundant regeneration of tendon cells. Marchand (1901) who reviewed Enderlen's actual microscopic sections came to a different opinion as to the healing process. He stated that most of the new tissue came from the sheath and surrounding connective tissues and that it was difficult if not impossible to distinguish between tendon cell mitoses and connective tissue cell mitoses. Marchand did not deny that tendon cells proliferated, but he did not believe that they performed an important part in the process of tendon repair. He concluded that the origin of the tissue made no great difference, since it eventually produced a structure functionally equivalent to tendon. Imoyashi (1925) who used special stains supported Enderlen's contention that the healing of the defect was due to tendon cell proliferation. He believed that he was able to distinguish between tenoblasts and fibroblasts by means of vital staining, and concluded that the tenoblasts came from the stumps and not from the connective tissue cells. Max Lange (1929) concluded from his experiments that the regenerative power of tendon itself was not great. He found that if the peritendinous and subcutaneous tissues were prevented from entering into the formation of tendon callus, "tendon regeneration" did not occur. Although he did not question the regeneration of tendon cells, he did not lay any stress on this regeneration in the process of tendon healing.

It is evident from the foregoing text, that despite extensive experimental histological studies, there was lack of agreement concerning even the tissues involved in the process of tendon healing. It was not until Garlock (1927), and particularly Mason and Shearon (1932), and Mason and Allen (1941) who presented well conducted studies, that a clearer conception of the processes of tendon healing evolved. They concluded that "both the connective tissues in and around the tendon, and the tendon itself, took part in the process of tendon healing and that both were of equal importance. Whatever the tissue was that united the tendons, whether it was simply a scar or true tendon, it behaved as tendon and possessed the strength of tendon." The views expressed in the following sections are based mainly on the articles published by the above authors. However, in the course of the experimental work involved in this thesis, opportunities arose for confirming certain opinions expressed and these have been included in the discussion.

## TENDON HEALING

Three tissues participate in tendon repair - the tendon itself, the connective tissues in and on the surface of the tendon, and the connective tissue surrounding the tendon. Although the fundamental process of healing is similar in both tendons in sheaths and tendons in paratenon, the presence of a synovial sheath may considerably modify the course of healing. In sheath covered tendons, the thin synovial layer investing the tendon, the paucity of epitenon and endotenon together with their limited blood supply is not conducive to adequate connective tissue regeneration. Clinical experience has repeatedly shown the mediocre healing power of both sutured tendons and tendon grafts within the synovial sheaths.

This observation is particularly evident in tendons in which a good mesotenon is lacking, or where the tendon is entirely surrounded by a dense fibro-osseous tunnel.

The process of repair in tendons in paratenon takes place much faster and more effectively than in tendons in sheath formation. The peritendinous and intratendinous connective tissues have a relatively good blood supply, and adequate union is secured earlier and with greater consistency.

## THE PROCESS OF TENDON HEALING FOLLOWING SUTURE AND IMMOBILISATION

According to Mason and Shearon (1932), when the ends of a divided tendon are approximated and sutured the process of tendon healing may be divided into three consecutive phases.

(a) The phase of exudation and fibrinous union.

(b) The phase of fibroplasia.

(c) The phase of maturation or organising differentiation.

### (A) THE PHASE OF EXUDATION AND FIBRINOUS UNION

Immediately following tendon suture the defect between the stumps is filled by a red gelatinous exudate which is derived from the tissue fluids and capillaries. The cellular contents of the exudate consist of blood elements. During the next few days considerable swelling appears due to oedema and proliferation of the intratendinous and peritendinous tissues. The tendon stumps become swollen, lose their "mother of pearl" sheen and appear pink or red owing to hyperaemia. The stumps are practically always separated, the degree of separation depending on the type of suture and the adequacy of the immobilisation. Microscopic examination at this stage reveals that the connective tissue elements proliferate and send out fibroblasts which invade the homogenous jelly-like substance. The fibroblasts soon contract to form connective tissue fibres. This proliferative process does not come from the tendon cells, but is derived from the tendon sheath, paratenon, epitenon and endotenon.

## (B) THE PHASE OF FIBROPLASIA

During the second week, connective tissue proliferation is at its height. Swelling of the tendon junction increases to its maximum and although the swollen fibroblastic splint uniting the stumps looks formidable, it is devoid of strength. Tendon fibres and cells are now conspicuous, and between the tenth and fourteenth days are seen bridging the gap. Until the ends of the tendons are united by tendon fibres of collagen, the junction can easily be ruptured. The fusiform tendon union is adherent to the surrounding tissues, from which it derives an additional and important blood supply.

The third week is marked by the production of tendon collagen fibres which cross the gap. The union though still swollen, becomes less vascular and firmer and a fair degree of strength is present which is mainly dependent on the stronger tendon collagen fibres. The collagen fibres, in response to tendon tension are longitudinally disposed. The tendon tension results from physiological muscle tonus. At the end of the third week, the adhesions between the tendon and the surrounding tissues begin to loosen and may be separated with ease by blunt dissection.

## (C) THE PHASE OF MATURATION OR ORGANISING DIFFERENTIATION

The fourth week may be considered as the stage of maturation or organising differentiation. Most of the swelling resolves, and the tissues regain their normal appearance. The original defect is now bridged by strands of tough fibrous-looking tissue, the junction is strong and will withstand tension of many pounds. Microscopically, the stumps are still very cellular and mitoses are not infrequent. It is not possible however, to determine the point where the stumps end. The tissue is definitely orientated in line with the pull of the tendon with evidence of the formation of tendon bundles as found in the normal tendon. The connective tissues surrounding the sheath though still hypertrophied,

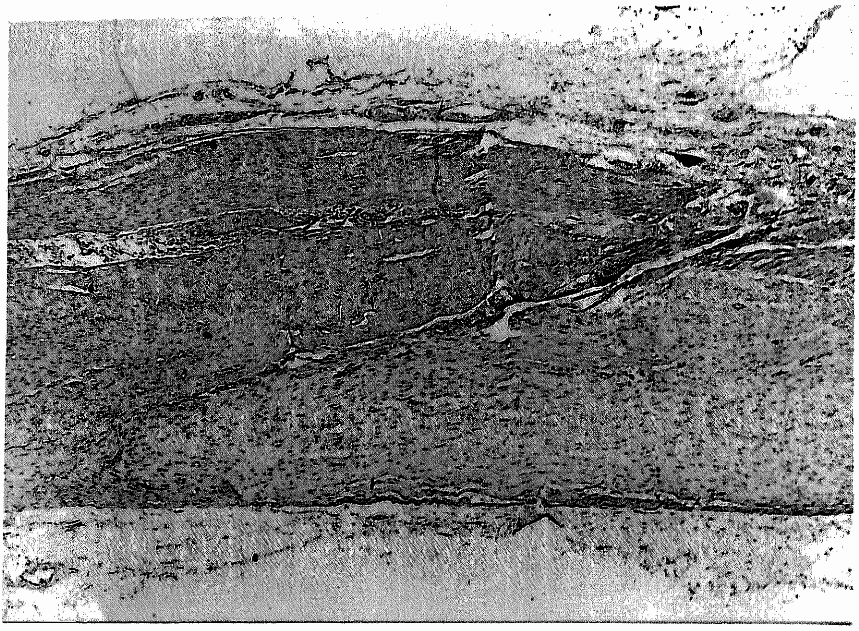

Fig. 22 Photomicrograph of a healing tendon (palmaris longus) to show the effect of immobilisation. (C. Aethiops).

Haematoxylin and Eosin X 40

A longitudinal section of the suture line of a tendon that had been immobilised for 20 days and allowed functional activity for 10 days. The peritendinous connective tissues are loose and the periphery of the tendon well demarcated.

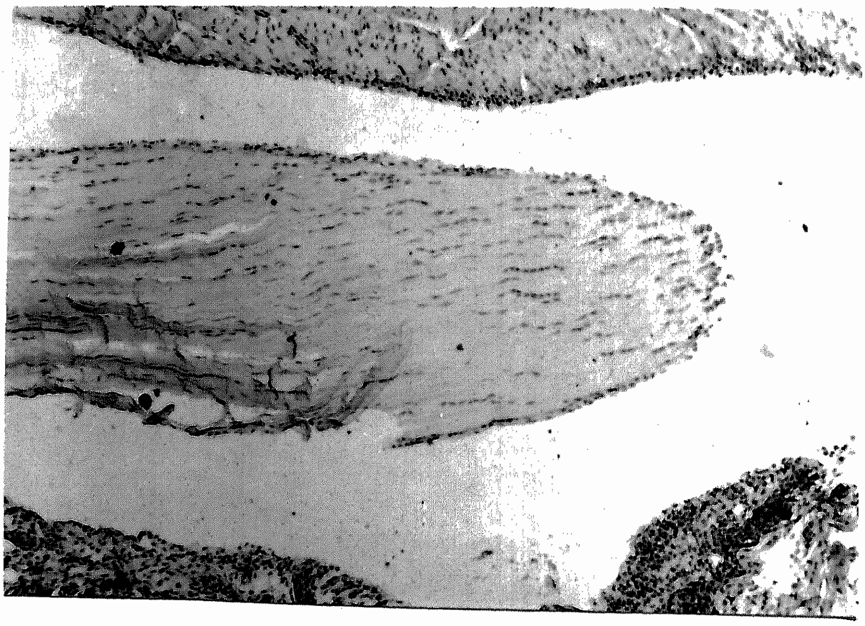

Fig. 23 Photomicrograph of a tendon severed in a sheath (C. Aethiops).

Haematoxylin and Eosin X 100

A longitudinal section of the proximal end of the flexor digitorum profundus tendon in the digital sheath. The tendon was divided 87 days previously but not sutured. Note that the tendon lies free in its sheath, the free end is rounded, and there is no evidence of proliferation.

begin to separate from the tendon, and although still attached by numerous fine adhesions resume their function of gliding. (Fig. 22).

## THE PROCESS OF HEALING IN TENDON GRAFTS

The basic histological process of healing in both end-to-end tendon suture and tendon grafts, is similar, but the repair in the latter lags behind the repair of a normal tendon by only a week.

A free tendon graft is initially nourished by the surrounding lymph and tissue fluids until it finally becomes vascularised. The peritendinous connective tissues of both graft and stump soon proliferate, fuse, and are mainly responsible for bridging the defect at this early stage. The surface of the graft lives, but in the centre of the tendon foci of necrosis become apparent, which are most conspicuous at the end of the first week. Until the seventh day there is little proliferation of the intratendinous tissues of the graft. In the stumps, however, the intratendinous tissues begin to proliferate and invade the graft. After eleven days, the foci of necrosis in the graft become replaced by regular tendon cells and fibres. During the first two or three weeks the tendon graft is considerably swollen, vascular and adherent to the surrounding tissues. After three to four weeks, the oedema and vascularity subside, and the peritendinous tissues loosen up and gliding becomes possible. Bunnell (1948), who had personally used as many as 950 free tendon grafts, stated that they lived permanently and hypertrophied in response to demands put upon them. With the passage of time the graft contracts, and when utilising a graft to bridge a tendon defect, a segment longer than the length of the defect should be employed.

## THE PROCESS OF REPAIR FOLLOWING NON-SUTURE OF TENDONS

When a tendon is severed, its ends retract, the degree

Fig. 24 Photomicrograph of a tendon severed in Paratenon (Human).

Haematoxylin and Eosin X 30

Case History: An adult male sustained a stab wound of the wrist with division of the median nerve. On excising the wound, the median nerve and palmaris longus tendon were found to be completely severed. The wound was sutured, and eighteen days later, a secondary suture of the nerve was performed.
At the second operation, the proximal end of the palmaris longus tendon was found to have retracted an inch, and the defect was bridged by a firm, yellowish gelatinous tissue which was adherent to the sheath of the median nerve. The tendon was not sutured because the ends could not be approximated without considerable tension. Neither was suture of the tendon necessary, for the functional disability following division of this tendon is nil. The photomicrograph is a longitudinal section of the proximal tendon stump. Note the proliferating tendon, advancing in the form of psuedopodia, and invading the fibroblastic splint in an attempt to bridge the defect. Note the marked cellularity and vascularity of the fibroblastic splint or callus.

of retraction being greater in tendons in sheath formation than in tendons in paratenon. The tendon ends, if severed in a sheath, become smooth and rounded and in the absence of infection make no attempt to bridge the gap. (Fig. 23). If severed in paratenon however, the surrounding paratenon proliferates and sends out pseudopodia in an effort to re-unite the tendon. (Fig. 24). If the separation is not great, the divided ends will unite albeit in a lengthended condition. Eventually contraction occurs so that continuity of the tendon is re-established. Frequently, especially if the separation of the severed ends is marked, the proliferating tendon will attach itself firmly to whatever it touches and will anchor the tendon end. This may be detrimental to the individual, in that firm attachment may immobilise the common muscle which moves the tendons of the other fingers and thus hinder function. This is frequently seen after amputation of a finger; the tendon which becomes attached to the stump has a limited amplitude of motion and restricts motion of the tendons of the other fingers. Under no circumstances should the divided ends of antagonistic tendons be sutured over the stump of the amputated bone.

Up to two months following tendon division, the separated ends may be drawn together and a direct suture performed. (Bunnell 1948). Following the lapse of longer periods of time, however, muscle contracture supervenes consequent upon disuse, and direct suture will be difficult or impossible. Tendons, like muscle and bone undergo degenerative changes following prolonged immobilisation. They become soft and thick, yellow and friable and are not suitable for use in tendon grafting.

## THE RATE OF HEALING IN IMMOBILISED TENDONS

Mason and Allen (1941) who experimented on flexor tendons of the wrists of dogs stated that the rate of tendon healing as determined by measurements of tensile strength exhibits

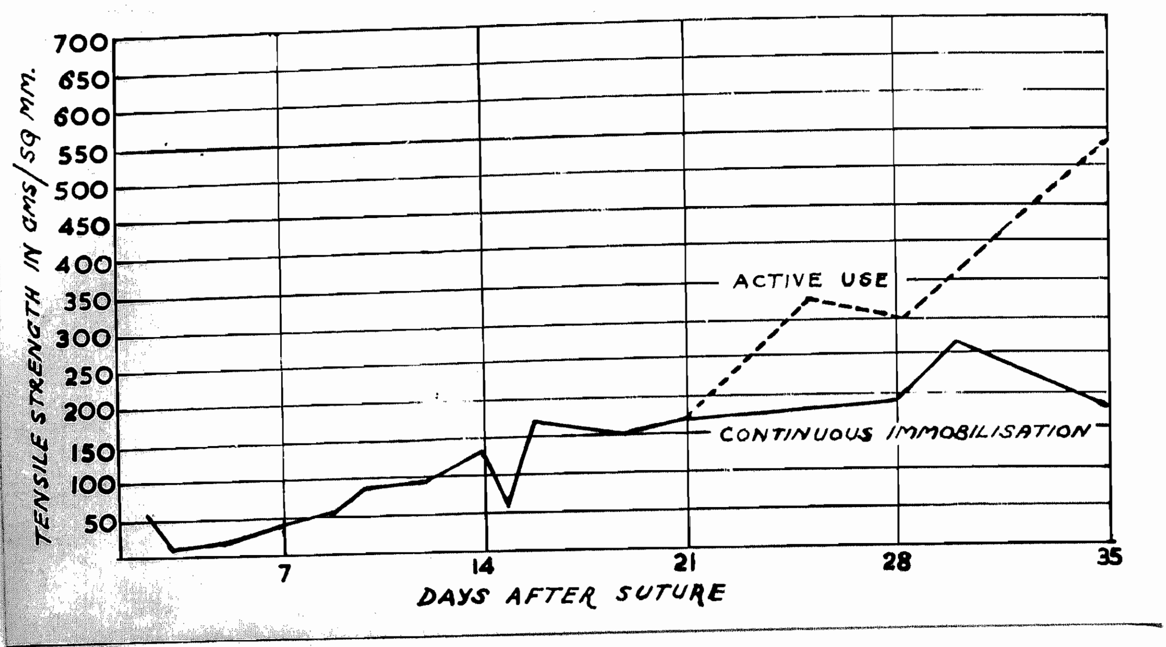

Fig. 25 The Tensile Strength (in gms. per sq. mm.) of healing flexor tendons in dogs, two to thirty five days following suture. (Mason and Allen 1941).

The continuous line represents tendons continuously immobilised. Note that during the first four or five days following suture, the tensile strength of the tendons dropped to considerably less than that found to be present immediately following operation. This was due to the fact that following tendon suture, the tendon ends become soft and are held together by a gelatinous exudate which possesses a very minimum of tensile strength. On about the fifth day, the tensile strength of the tendons showed a steady increase and reached a plateau on the fourteenth or sixteenth day. This was maintained until about the nineteenth day. A second plateau was reached about the twentyfirst day which with minor fluctuations persisted for the following two weeks. The slight fall in tensile strength noted at the end of five weeks suggested atrophy of the tendon at the suture line, the result of disuse. Tensile strength was not determined for periods longer than thirty five days.

The interrupted line represents the tensile strength of tendons which were subjected to immediate active use following three weeks immobilisation. Note the marked increase in tensile strength.

three phases which coincide with the three stages of histological healing. (Fig. 25).

During the stage of exudation and fibrinous union, there is a rapid diminution in tensile strength which lasts for about five days. Immediately following the repair of a divided tendon, the strength of the union is that of the suture material. The holding power of the tendon rapidly and progressively diminishes owing to softening, and by the second post-operative day the sutures begin to ease out of the tendon, resulting in varying degrees of retraction. The extent of retraction depends on the degree of tendon tension, the duration and efficiency of immobilisation, and the type of suture employed. The tensile strength of the union, reaches its lowest level on the third day but by the fifth day begins to increase. By the ninth day the tensile strength of the union approaches the tensile strength which was present immediately following suture i.e. the strength of the suture material used.

The next phase of healing is marked by an increase in tensile strength which reaches a plateau on about the sixteenth day. This phase coincides with the stage of fibroplasia.

The third phase coincides with phase of maturation and is also characterised by an increase in tensile strength which probably starts between the nineteenth and twenty-first days and continues for an undetermined period of time. It is during this phase that functional activity has a beneficial effect.

## THE EFFECT OF FUNCTION ON THE RATE OF HEALING

Wolf was the first to introduce into clinical surgery the concept that the final form of tissues was related to the stresses and strains imposed during healing. Although he had in mind the effect of function on the final form of bone, his conception of the functional influence on healing processes

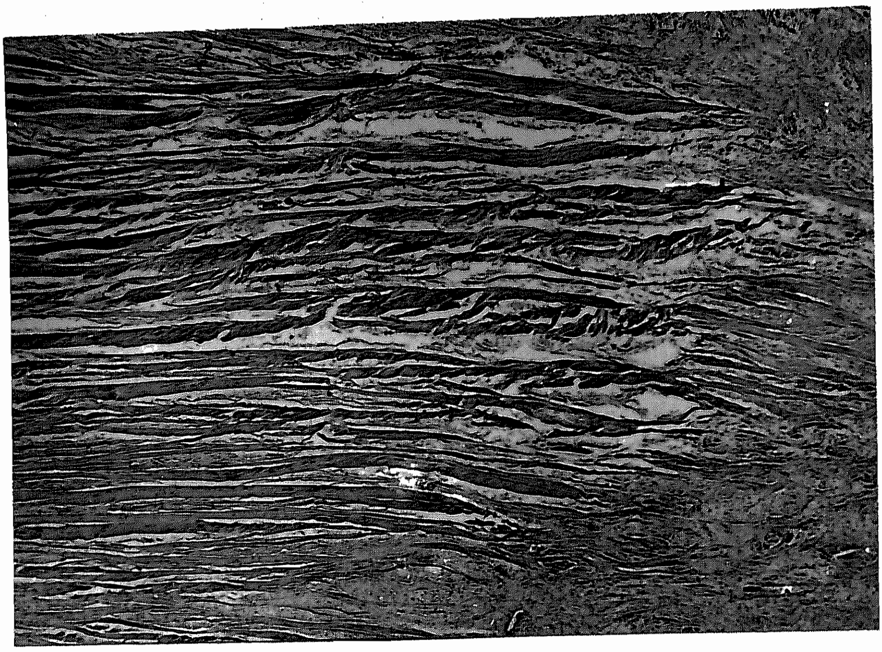

Fig. 26 Photomicrograph of a tendon to show the effect of functional activity on the growth of tendon fibres. (C. Aethiops).
Haematoxylin and Eosin X 130

A longitudinal section of the growing end of a sutured tendon (palmaris longus) which was immobilised for seventeen days and then subjected to active use for a period of two weeks. Note the axial alignment of tendon fibres. Cellular detail is poor on account of faulty fixation of the specimen. Compare with Fig. 27.

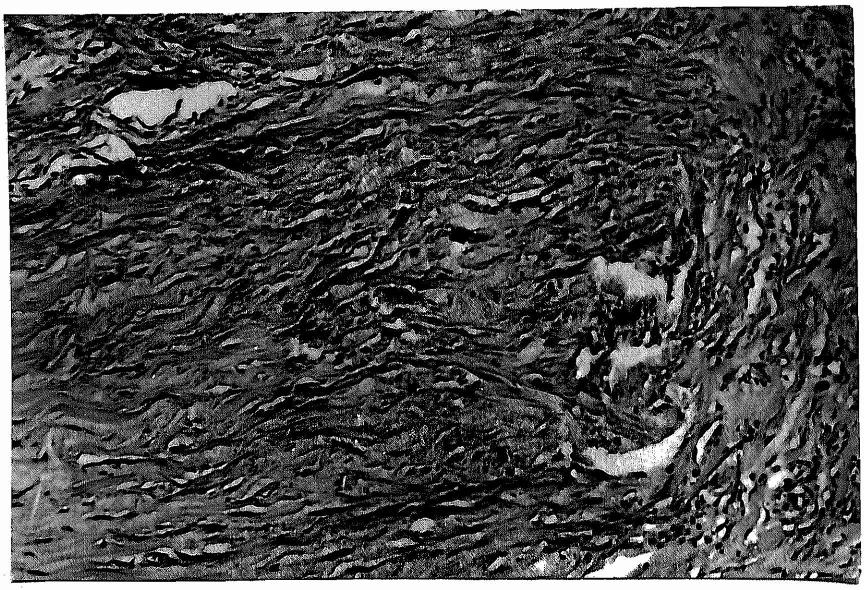

Fig. 27 Photomicrograph of a tendon to show the effect of prlonged immobilisation on the growth of tendon fibres. (C. Aethiops).
Haematoxylin and Eosin X 130

A longitudinal section of the growing end of a tendon (palmaris longus) which was immobilised for 31 days, but not subjected to active use. Note the disorientation of tendon fibres and cells.

Fig. 28 Photomicrograph of healing in a tendon (palmaris longus) to show the effect of immediate active use. (C. Aethiops).

Haematoxylin and Eosin X 80

A longitudinal section of the suture line of a tendon that had been subjected to active use for a period of thirty days without immobilisation. Note the marked vascularity and cellularity of the peritendinous connective tissues and its adherence to the tendon which also shows marked cellularity and vascularity. Compare with Fig. 22. Macroscopically, the tendon junction was fusiform and adherent to surrounding tissues.

had a wide application in general biology.

Tension is an important factor in tendon regeneration, for under its influence, the nuclei and fibres align themselves in rows parallel to the line of stress (Fig. 26) whereas if this functional influence is absent, the new tissue remains disorderly and non-orientated (Fig. 27), and union of the tendon ends is considerably delayed and feeble. Mason and Allen found that function was beneficial during the third stage of healing. (Fig. 25). During the first and second stages, that is up to the fifteenth day, the union of a functioning or mobilised tendon was no greater than that at the junction of a tendon which had been carefully protected by immobilisation. On the contrary and most significant they found that a mobilised tendon was more irritated, swollen and adherent to its sheath (Fig. 28), and if undue tension was imposed the tendon frequently separated at the suture line.

From the fifteenth to the twenty-first day after suture, both the functioning and immobilised tendons increased equally in strength. Beyond this period however, the immobilised tendon did not increase in strength whereas the exercised tendon continued to strengthen in response to function.

## THE PRACTICAL APPLICATION OF FUNCTION DURING HEALING

A consideration of the facts presented above indicates that functional activity during the first fifteen days is apparently detrimental to the degree of union and gliding ultimately obtained. Clinically therefore, exercise should be forbidden for the first fifteen to twenty days following tendon suture. Thereafter, restricted or quarded exercises should be instituted for a period of a week followed by more active motion. After the fourth week the danger of disruption has passed and the more the tendon is exercised up to a reasonable degree, the greater will be its mobility. Pulvertaft (1948), commenting on Mason and Allen's opinion that exercise should be forbidden for the first fifteen to twenty days following tendon suture stated that their work was not "entirely confirmed by the observation of post-operative progress. I have found that some of my better results after flexor tendon grafts have followed an early commencement of active movements. A few cases which have been immobilised for 21 days have shown very delayed or incomplete recovery". Pulvertaft agrees however that "no reliance can be placed on the tendon union until well into the fourth week and if early movements are to be encouraged, the technique of suture and the materials used must be faultless, as the strain falls directly upon the suture line."

# CHAPTER 3

# EXPERIMENTAL RECONSTRUCTION OF TENDON SHEATHS

## AN HISTORICAL REVIEW

The incapacitating and often disastrous consequences of adhesion formation, culminating in complications such as intestinal obstruction, epilepsy, stiff and painful joints, and useless fingers have long been appreciated. Numerous efforts have been made to preserve the integrity of the potential body spaces such as the peritoneal cavity, the subarachnoid space, joint cavities and tendon sheaths, but despite the observance of rigid aseptic, atraumatic and haemostatic techniques, adhesions still formed.

## THE FORMATION OF ADHESIONS

Adhesions are formed by the growth of connective tissue which has been stimulated to activity by irritation. Any injury inflicted upon the delicate endothelial membranes of serous cavities, whether due to the trauma of an accident, the knife of a surgeon or infection, inevitably results in some reaction followed by exudation. Perhaps a haemorrhage may occur, so slight as to pass undetected, or demand no attention. The wound having been closed, the walls of the space or cavity readily become glued together by the exudate or clot. Generally, absorption is accomplished through the complete or partial disintegration and liquefaction of the reactionary exudate. Should the exudate be slow to absorb on account of inadequate action on the part of proteolytic ferments or the macrophages, the presence of excessive quantities of exudate, or continuous irritation, organisation of the exudate takes place through infiltrating connective tissue cells and blood vessels which utilise the fibrin meshwork as a scaffolding. The dead space is thus obliterated but at the expense of fibrous tissue or adhesion formation. Owing to the difficulties encountered in preventing adhesions endless attempts have been made to find a substance, which when introduced into serous cavities, would prevent the apposition of adjacent surfaces by clots of fibrin or blood, and hinder connective tissue growth between them.

During the latter part of the last century, Maximow, Alferow and Sirzow, quoted by Prime (1913), used celloidin in experiments on growing connective tissues. They demonstrated that connective tissue could not grow unless it had a biologic medium through which it could infiltrate and that it was unable to bridge dead spaces without means of support. Although celloidin had been recognised and used for so many years it was not until 1913 that Prime published an article on its use in preventing the formation of adhesions. Until then it was found that the best results achieved in the prevention of cerebral adhesions were obtained where no foreign substance was introduced at all, and a stream of warm water allowed to flow gently over the operative field. This however gave results far from ideal, and it was felt that in order to achieve a more favourable outcome it was necessary to find if possible some substance, which when introduced and allowed to remain indefinitely would be non-irritating. The foreign materials which had been used previously were all irritants to a greater or lesser degree, and usually resulted in a condition worse than the one they were supposed to cure, stimulating rather than retarding the growth of connective tissue. Especially had this been the case where rubber, gold and silver foil, or animal tissue such as egg or Cargile* membrane were used.

To ascertain whether celloidin could be used to advantage in situations where adhesions were most apt to form, the brain, joints, tendons, and nerves were selected as the most suitable places to introduce the substance. The results of Prime's experiments demonstrated that chemically pure celloidin did not produce a typical foreign-body reaction, and that the surface of the celloidin became coated with a smooth tissue

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*Cargile membrane is chromicised pig's bladder. (Mayer 1951, personal communication).
Stedmans Medical dictionary states that Cargile membrane is prepared from ox peritoneum.

whose flattened cells resembled those lining the walls of serous cavities.

Although Prime mentioned the use of celloidin in tendon repair, he gave neither details of the experiment nor the results.

### FAT, FASCIA, VEINS, ROLLED SILVER, CARGILE MEMBRANE

Mayer (1916) determined the effects of ensheathing tendons with fat, fascia, veins, cartilage, thin tubes of rolled silver and Cargile membrane. In all instances, except where the Cargile membrane was used, the adhesions proved firmer than where nothing was inserted to prevent their formation. Mayer gave no further information concerning the use of vein grafts in his publication.

### CELLOIDIN

Mayer and Ranshoff (1936) while continuing their studies on the prevention of tendon adhesions had their attention drawn to the work of Prime. They stated that Prime "made no mention of the possible application of celloidin in tendon surgery." In fairness to Prime it may be stated that he did mention the possible value of celloidin in tendon surgery although he gave no details.

Mayer and Ranshoff implanted tubes of chemically pure celloidin around the Achilles tendon of the rabbit. The results obtained indicated that a sheath could be built up around the tendon, which in many respects resembled the normal lining of a tendon sheath. These two workers thereupon made celloidin tubes of varying sizes for use in the reconstruction of adherent digital tendon sheaths. The tubes were highly polished and corresponded to the shape of tendon sheaths of different hands. Their operative technique involved two stages. The first stage of the operation consisted of complete excision of the adherent tendon and sheath followed by implantation of the celloidin tube in the digit. The tube was maintained in position by suture of the ends of the resected tendon to the ends of the tube. The subcutaneous tissues were carefully united over the tube to give it complete coverage, and the skin accurately sutured. The affected finger was then immobilised with a light splint and the second stage of the operation undertaken four to six weeks later. At the second stage, "in every instance the tube had been found completely enveloped by a smooth, glistening membrane whose surface closely resembled the normal lining of a tendon sheath. Surrounding the tube a small quantity of clear straw-coloured fluid was found similar in appearance and consistency to the secretion of the normal tendon sheath." Generally a tendon graft from the flexor digitorum sublimus of the injured finger was utilised, and if the muscle of the damaged tendon appeared to have degenerated, the flexor digitorum sublimus tendon of the adjacent finger was used to activate the digit. The after treatment consisted of splinting the affected finger for a period of ten days followed by active movements and sinusoidal stimulation of the muscles. The authors stressed that the impression might be gained by some that the celloidin tube exerted a magic power to transform a disabled finger into one with normal function. It was obvious that such an impression was erroneous. The celloidin tube was only one detail in a series of extremely complex, delicate surgical procedures. As to the end results, the authors stated that at first, motion of the transplant was pitifully slight, but increased from day to day, and that they were able to secure gratifying end results.

## GLASS RODS

Owing to the difficulty in procuring commercially manufactured celloidin rods, the involved technique and length of time required in their preparation, Thatcher (1939) and his associates who were working along similar lines to Mayer and Ranshoff experimented with glass stirring rods. The glass rods were curved to conform to the shape of the flexed finger and in this respect were an improvement on the straight celloidin rod. They were five-thirtyseconds of an inch in diameter, cut to suitable lengths, and their sharp ends rounded off in a gas flame. The glass rods caused no foreign body reaction in the fingers, but they carried the possibility of breakage. Although this hazard was avoided, the fear of such an accident was always present, and this led to the trial of stainless steel.

## STAINLESS STEEL RODS

Following a successful trial, during which no tissue reaction occurred, Thatcher used stainless steel rods extensively. The rods were oval in shape to conform to the natural shape of the tendon, highly polished and had a groove filed near each end for fixation to the tendon stumps. Examination of the stainless steel rods after removal revealed no surface corrosion, and smooth surfaced tunnels had formed in the adjacent tissues.

In his publication, Thatcher did not mention his results in terms of function nor the number of cases treated. Bunnell (1948) commenting on Thatcher's work stated that microscopically a synovial sheath was actually demonstrated, but in a personal communication, Thatcher (1951) stated that "a number of years ago, I had a small section of this sheath examined in the pathological laboratory. Unfortunately, I have no record of their findings. I have used this method for about 18 years and find it of value in hand surgery."

## STAINLESS STEEL RIBBONS

Milgram (1947) temporarily inserted thin flat sheets of stainless steel ribbon between tendons and surrounding cicatrical tissue, so as to establish a "synovial lined cleavage". He advised that the metal be removed within three weeks to prevent excessive scarring. He gave no details of the results.

## TYGON (S33 - 1)

One of the disadvantages of stainless steel or other metal rods was the rigidity of these substances. During the 4 to 6 weeks that these tubes remained in the finger, the digital joints were immobilised. The resultant stiffness presented a difficult problem in the subsequent mobilisation of the joints. Furthermore, the rods could only be placed in a well nourished digit because the rigid tube might impair the circulation of the digit if the overlying skin were not sufficiently elastic.

Hanish and Kleiger (1948) aware of the disadvantages of rigid rods decided that a flexible non-irritating material that could induce a synovial-like reaction would be of great value. Smooth tubes of tygon, a polyvinyl-chloride resin derivative which is flexible and chemically inert, were implanted subcutaneously in the abdominal walls of two adult guinea pigs and four adult rabbits. In the same animals tygon tubes were implanted around the Achilles tendon and in the latter sites were re-implanted as many as three times to study the extent of scar production. The specimens which included the tube and its encircling sheath were removed en-bloc after 21 days in the guinea pig, and 30 days in the rabbit.

### RESULTS

On naked eye examination, the tubes were found to be enveloped by a discrete greyish-white elastic sheath. The tubes were easily removable and the tunnels formed were shiny, smooth and "well lubricated." Microscopically, the sheaths were lined on their inner surfaces by flattened mesothelial-like cells, and the walls of the sheath composed of parallel layers of cells of a fibroblastic type. Small areas of haemorrhage were observed in the specimens, the reaction being more marked in the rabbit. Leucocytic infiltration or foreign body giant cells were not evident. Photomicrographs support the evidence claimed, and in summing up the authors stated that the production of tendon sheaths using this substance warranted a clinical trial.

## DISCUSSION

Hanish and Kleiger noted that the artificially produced sheaths were "well lubricated", and the impression might be gained that the presence of the fluid was a desirable feature in that it simulated the lubricating properties of a synovial sheath. It is possible that the presence of the fluid was a reactionary response, indicative of irritation produced by the plastic tubes, and therefore unphysiological.

## FASCIA LATA

Cleveland (1930) using fascia lata, attempted the reconstruction of the digital sheath of a finger in a girl who had had a suppurative tenosynovitis five years previously. Prior to the operation there was no active flexion in the digit. Through an incision along the whole anterior extent of the finger he exposed and excised the fibrous and adherent tendon and sheath and bridged the tendon defect with a tendon graft. A strip of fascia lata was excised from the thigh and folded around the reconstructed tendon with its smooth surface adjacent to the tendon. At each of the joints small strips of fascia lata were drawn over the tendon and its sheath and sutured to the periosteum on each side to act as restraining bands. Active movements were begun the day after operation. Two and a half years later the patient was found to have a useful finger. There was a full range of movement at the metacarpo-phalangeal joint, 70% of the full range at the proximal interphalangeal joint, and 30% of the normal range of movement at the distal interphalangeal joint.

Cleveland ascribed the large measure of success in this one case to :

1. The excellent condition of the skin and the subcutaneous tissues.

2. The free motion of the interphalangeal joints prior to operation.
3. The introduction of an adequate gliding mechanism around the new tendon.
4. The placing of restraining bands at the interphalangeal joints to prevent bowstringing.
5. Early active movements.

## DISCUSSION

It would be difficult to assess from this one case what benefit really accrued from the fascia lata solely. A tendon graft without using fascia lata might possibly have achieved a similar result.

## AMNIOPLASTIN

Penfield, Humphreys and Chao (1940), using amnioplastin were successful in preventing adhesions in experimental brain wounds in cats, and in cerebral operations in man. Lambert Rogers (1941) reported successful results following its use in the treatment of peripheral nerve injuries, while Law and Phillip (1941) reported on its use as a conjunctival graft. Although Penfield suggested the possible value of amnioplastin for the prevention of tendon adhesions, Pinkerton (1942) was the first to report on its results in tendon surgery.

Human amnion is a fine membrane composed of a few layers of mesenchymal stroma covered by a single layer of entoderm. Penfield's method of preparing amnioplastin was used. This consisted of washing the membrane to remove all blood and mucus, immersing it in 70% alcohol, drying it in sheets, and sterilising it by boiling for 20 minutes in distilled water. It was then kept in sterile normal saline for 20-30 minutes before use. The final product was a thin, acellular, transparent pliable membrane.

## RESULTS

Pinkerton used amnioplastin for the prevention of adhesions in the digital flexor sheath and published details of the results obtained in four cases. He stated that the results had been satisfactory up to three months following operation, and that no gross inflammatory reaction was noted in any of the cases in which the amnioplastin had been used.

## CELLOPHANE

Wheeldon (1939) published a report on the use of cellophane as a suitable substance for the prevention of tendon adhesions. Having achieved excellent results in arthroplastic procedures without obvious evidence of tissue irritation, Wheeldon elected to use cellophane as a permanent tendon sheath in a case of a cut extensor pollicis longus tendon. The cellophane was transparent and .00088 inches thick. The wound healed by primary intention and the functional result was recorded as "good."

## DISCUSSION

The functional result of suture of an extensor pollicis longus tendon by a simple method is excellent, and it is therefore difficult to assess the value derived from the use of cellophane in this one case.

Farmer (1947) on the other hand, reported that the results of cellophane wrapped around a tendon were not good. McKeever (quoted by Bunnell 1948) used a special cellophane (300 PUT 71 Du Pont) in a tendon repair and reported that the substance fragmented and collected in wads but that it was not irritating and a good cleavage plane was established. Further reports on the use of cellophane will be found on page 47.

## TUNICA VAGINALIS

Wilmoth (1929) attempted the reconstruction of tendon sheaths using tunica vaginalis.

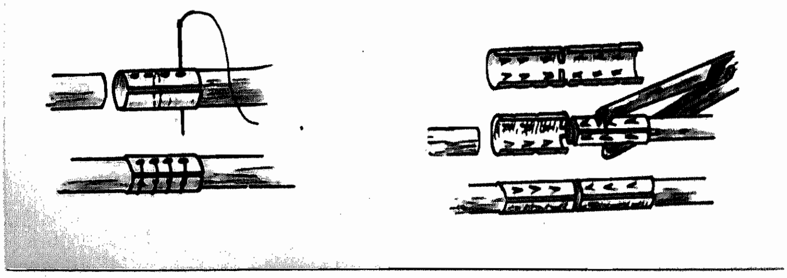
Tunica vaginalis is a thin membranous structure made up of two layers; an inner one formed by a single layer of flattened endothelial cells, and an outer one composed of fibrous connective tissue containing elastic fibres. The presence of the elastic tissue permits the distension of the tunica vaginalis to a marked degree and when transplanted, retains its ability to secrete a serous fluid similar in appearance to the synovial fluid of tendon sheaths. It was probably this latter factor that stimulated Wilmoth to experiment on the artificial reconstruction of tendon sheaths. Initially, Wilmoth experimented on tendons in the leg of the dog. Four months after the operation it was noted that the transplanted tunica vaginalis survived, although not without adhesions to the tendon, but as far as could be determined, the adhesions did not tend to limit the motion of the tendon.

Wilmoth then attempted to reconstruct the digital flexor sheath in six patients. The tunica vaginalis was removed through high scrotal incisions and generally sufficient material was available for the reconstruction of two tendon sheaths. With the exception of one case, all the operations were secondary repairs. The following were the results in his cases:-

Case 1. Loss of approximately 20% of the normal range of movement.
Case 2. Loss of approximately 25% of the normal range of movement.
Case 3. Almost full flexion.
Case 4. Loss of 50% of the normal range of flexion.
Case 5. Result stated as satisfactory.
Case 6. Nearly complete flexion.

## DISCUSSION

The above results appear impressive, but examination of the method of evaluation reveals that the results may be very misleading. Instead of stating the loss of range of movement at each of the joints, which is the usual procedure, the functional results are expressed as an average percentage loss of the combined range of movement at all three digital joints. To illustrate the possibility of misconception, consider a hypothetical case in which there is a full range of movement at the metacarpo-phalangeal joint, 50% loss of movement at the proximal interphalangeal joint, and a 100% loss of movement at the terminal interphalangeal joint. An assessment of the result by the method of Wilmoth would reveal an average percentage loss of movement of 50% and superficially



(a) (b)

Fig. 29. The metal anastomosis tubes used by McKee.

In (a) the tendon was anchored within the tube by transfixion sutures passing through the perforations on one side, through the tendon, and then out through the perforations on the other side of the tube. In (b) the presence of spikes in the tube obviated the necessity for sutures.

this might be considered a fair result, whereas when considering the total loss of movement at the distal interphalangeal joint, the result would be classified as functionally poor.

Loss of flexion at the metacarpophalangeal joint in digital flexor tendon injuries is unusual. The lumbricals which are responsible for flexion at this joint are seldom injured, on account of the protection afforded them by the deep insertion of the tendon into the dorsal expansion hood. It is therefore not unreasonable to assume, that in Wilmoth's series, flexion at the metacarpophalangeal joints was not grossly impaired as the result of injury, and thus, his method of assessing the results is open to criticism.

The use of tunica vaginalis for the reconstruction of tendon sheaths had certain disadvantages; two operations were necessary and the tissue was available in limited quantities, and in the male only.

## METAL ANASTOMOSIS TUBES

The principle of immobilising tendons until firm natural repair has taken place, and the principle of instituting early active movements to reduce adhesions appear to be opposed to one another. McKee (1945) in an attempt to reconcile these two desiderata made use of a metal anastomosis tube in a two stage procedure.

The tubes employed were made of fine gauge malleable stainless steel or tantalum, half an inch long and three-sixteenths of an inch in diameter. They were split in their whole length so that they could be removed later, and had several holes perforated in their sides through which sutures could be passed. The tendon was anchored within the tube by transfixion sutures passing through the perforations on one side, through the tendon in the tube, and then out through the perforations on the other side of the tube. Later a modified type of tube with kick up spikes in its lumen was used, so as to avoid the use of sutures altogether (Fig. 29).

During the interval of five weeks between the two stages, the finger was kept splinted in a light plaster cast for the first three weeks, so as to allow union to take place without strain on the suture line. The second stage of the procedure consisted of exposing the tube, removing the sutures and then opening the tube along the line of the slit and removing it from the site of the anastomsis. Adhesions that formed around the tube were often dense, but the encirclement of metal around the tendon kept the site of anastomosis free. The digital sheath was not sutured and the wound was closed by suturing the skin only. Vigorous active movements were begun the day following the operation without fear of the tendon ends separating.

### RESULTS

The tendon ends readily united in the tubes by linear scars, and after the tubes had been removed the union was so accurate that it was difficult to make out where the tendons had been severed. Bands of fibrous tissue actually grew out through the perforations in the tube, and these had to be divided at the second stage of the procedure, undertaken some five weeks later.

McKee used this method in six cases and stated that "the results were fairly good."

### DISCUSSION

The results were not expressed in terms of movement and it is therefore difficult for an independent observer to evaluate the method. A disadvantage in the use of metal anastomosis tubes was the necessity to perform a second operation for their removal, a procedure which inflicted additional trauma and possibly paved the way for fresh adhesions.

### FIBRIN FILM, AUTOGENOUS FASCIA, GELFOAM, OXYCEL, CELLOPHANE

Weckesser et al (1949) conducted a comparative study of various substances to determine their efficiency in the prevention of adhesions around tendons. The following materials were studied in experiments on dogs:-

(1) Human fibrin film.

(2) Bovine fibrin film.

(3) Autogenous fascia, derived from the fascia lata of the thigh.

(4) Gelfoam.

(5) Oxycel cotton.

## THE METHOD

The flexor carpi ulnaris tendon of each leg was exposed through a cruved lateral incision just above the paw. An Allis' forceps was drawn over each tendon eight times to traumatise its surface following which two steel wire markers were placed one inch apart under the tendon through adjacent tissues. A one and a half inch length of the material to be tested was wrapped around the one tendon and the two pieces of steel wire were tied loosely around the material and tendon. The material projected one-fourth of an inch beyond each wire marker. On the opposite leg, the control limb, only the wire markers were tied around the tendon. Three to four weeks later, through small skin incisions the wire markers were identified. The segment of tendon between the wire markers was not disturbed. The tendon lying proximal and distal to the wire markers was exposed, freed by sharp dissection and divided without disturbing that portion of the tendon surrounded by the material under test. Haemostats were then applied to the proximal end of each tendon segment and the force required to pull the segment free, determined by means of a weight and pulley system. Except in earlier studies the affected limbs were not immobilised.

## RESULTS

All the materials used were effective in preventing the adherence of tendons. The human fibrin film, bovine fibrin film, and cellophane were about equally effective and gave the best results. (Table 2, Page 49). The gelfoam and oxycel were not very effective, owing probably to the fact that the tissues grew into the interstices of the material.

| MATERIAL | NUMBER OF DOGS | FORCE REQUIRED (IN GMS.) TO FREE THE TENDONS | | PER CENT. |
|---|---|---|---|---|
| | | EXPERIMENTAL TENDON | CONTROL TENDON | |
| HUMAN FIBRIN FILM | 12 | 867 | 4195 | 21 |
| BOVINE FIBRIN FILM | 5 | 805 | 3940 | 21 |
| CELLOPHANE | 6 | 950 | 4041 | 24 |
| AUTOGENOUS FASCIA | 11 | 2638 | 4422 | 60 |
| GELFOAM | 5 | 2160 | 3470 | 62 |
| OXYCEL COTTON | 6 | 3912 | 4458 | 88 |

Table 2. The average force required to free the experimental and control tendons, is tabulated in the third and and fourth columns. The last column indicates the percentage of the control force required to free the experimental segment of tendon for each material.

The reaction of the tissues where blood fraction films and cellophanes were used was greater than that about the autogenous fascia. This reaction is pertinent to the discussion which follows. Five of the twentyfour tendons surrounded by human fibrin film and one of the six tendons surrounded by cellophane showed signs of disintegration, indicative of interference with the nutrition of the tendon. In many instances a surface layer of cells resembling synovia had formed where the blood fraction films or cellophane had been used.

## DISCUSSION .

The results appear impressive, but the evaluation is open to criticism in that insufficient time was allowed before the final assessment. The materials which gave the best results, the human and bovine fibrin films, were still present, although usually thinned out, three to four weeks after implantation and showed evidence of surrounding tissue reaction. The presence of this tissue reaction indicated that the inflammatory process had not yet subsided and, therefore, insufficient time had elapsed for complete absorption of the fibrin films and the formation of fibrous tissue. It is not unreasonable to assume that had the various materials been allowed to remain in situ for periods longer than three to four weeks, adhesions would have formed and the results not have been so impressive. Following the complete absorption of the fibrin films, it was possible that the cleavage planes which were occasionally noted would have become obliterated because they were probably the result of exudate collecting between the fibrin films and surrounding tissues. With the passage of time the exudate would have absorbed with obliteration of the dead space.

## POLYETHYLENE *

In 1947 Grindley reported on a new plastic, polyethylene, a substance which was singularly non-irritating to tissues, flexible and readily adaptable to tube manufacture.

Gonzalez (1949), who prior to this time had been experimenting with cellulose acetate phthalate**, gelfoam and fibrin film, in an attempt to reduce adhesion formation following tendon repairs, had his attention drawn to this new substance. He experimented with polythene tubes around tendons within the flexor tunnels of the forelimb of the dog.

### THE METHOD:

Having first established that "the anatomy of the digital flexor mechanism of the forefoot of the dog was essentially the same as that in the human hand", he conducted a controlled experiment. It is of interest to note however, that Garlock (1927) who experimented on tendons in dogs, stated, "that this animal does not present any tendon structure similar to that found in the flexor tendon of the hand, i.e., the epitenon variety where the tendon glides freely in an encircling sheath."

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*Commercially known as Polythene this substance is simply a modified paraffin in which the chain molecules are very much longer than in ordinary household paraffin.

**This material is used commercially as an enteric coating for medicaments.

In order to immobilise the tendons during healing, Gonzalez took advantage of the fact that the slips of the canine flexor digitorum tendon were fused at the wrist. The first step in the operation consisted of the insertion of a stainless steel tension wire through the common flexor tendon with a proximal pull-out loop after the method of Bunnell. Fairly strong traction was exerted on the tension wire in order to relax completely the distal portions of the tendon, thus immobilising the sutured tendons during healing. The flexor sheaths of the 2nd and 5th digits of the same paw were then exposed, the flexor sublimus tendons excised, and the flexor digitorum profundus tendons divided. The polythene tube which was .08 mm. thick, 2 cm. in length and 4 mm. in diameter, was then threaded over either the distal or proximal tendon of the 2nd digit, and the tendon sutured. No polythene was placed around the anastomsis in the 5th digit; this digit acted as the control. The limbs were then immobilised with plaster casts. Following selected periods of immobilisation varying from eight to sixtyfive days the dogs were anaesthetised, the plaster casts removed, and tests for function and strength performed. The new incisions were longer than the original ones in order to mobilise the tendon slips in non-operated areas.

### Assessment of Function and Strength

In the intact normal dog, if the flexor sublimus tendon was excised from the tunnel and the vinculum dissected free of the flexor digitorum profundus, the distal portion of the profundus tendon moved to 3 to 8 mm. when longitudinal traction was applied to the tendon in the palm. After dividing the tendon distally, it could easily be withdrawn from the tunnel. If the experimental tendon behaved in a similar manner it was graded as normal - 3 plus function. Lesser degrees of function were graded as follows:- An excursion of 1 to 3 mm. of the distal tendon, and the ability to withdraw the tendon from the tunnel after distal division of the tendon using moderate to strong traction applied proximally - I plus function. No excursion of the distal tendon on traction and the inability to withdraw the transected tendon from the tunnel - O function. An unhealed tendon was graded as having O function.

The tendon segments were then excised, placed in a tensiometer and the tensile strength of the union determined by measuring the pull necessary to break the sutured tendon. The tensile strength was computed in grams per square millimetre, the cross sectional area of the tendon having been previously determined.

RESULTS

(1) The control tendons healed much earlier than the polythene tendons, the strongest healing occurring between the 15th and 20th day. No tendon surrounded by a polythene tube healed before the 29th day.

(2) The average tensile strength of the polythene enveloped tendons, immobilised for forty days or longer was 785 Gm. per square millimetre, whereas, the average tensile strength of the control tendons for the same period was 624 Gm. per square millimetre. These values demonstrated that with prolonged immobilisation strong healing did occur where the sutured tendons were isolated from the surrounding peritendinous structures by the polythene tubes.

(3) The functional results following immobilisation for 29 days or less using polythene tubes fell into the O classification. Where immobilisation was continued for longer than 29 days the functional ratings of 14 out of 16 polythene tubes were 2 or 3 plus, whereas no single control tendon was rated as better than I plus.

(4) No gross or microscopic reaction to the polythene tubing was noted.

## DISCUSSION

Gonzalez did not really evaluate tendon function. What was determined, was passive movement of the tendon only. The digital flexor mechanism is an integrated unit dependent for its function, not only upon a freely gliding tendon, but also on muscles capable of contracting, and interphalangeal joints having an adequate range of movement. The mobility of the interphalangeal joints was not determined, and it is quite possible that there was limitation of joint movement following the prolonged periods of immobilisation (at least 40 days) which were necessary for strong tendon healing. Furthermore, it will be recalled that the tendons were allowed to heal without tension, owing to the presence of tension sutures inserted through the common flexor digitorum profundus tendon. Muscles under constant tension for prolonged periods are bound to undergo degenerative changes, and it is conceivable that this complication occurred in the flexor digitorum profundi muscles of the experimental animals.

The method used for determining the passive excursion of the tendon calls for comment. Longitudinal traction was applied to the palmar portion of the tendon and the excursion of the distal end of the tendon noted and recorded in millimetres. A millimetre is a small unit of length and unless the force of traction applied to all the tendons was the same, tendon excursions were not comparable. In his publication, Gonzalez did not mention the nature of, or the degree of the force applied to the tendon, except to state that traction was moderate to strong. It is therefore assumed that manual traction was applied to the tendon, and therefore it was difficult or impossible to exert a constant longitudinal force on all the tendons.

Finally, his conclusion stating that "tendons blocked away from the extratendinous tissues by polythene tubes following primary suture within the flexor tunnels, and immobilised forty days or longer approach normal function while control tendons approach non-function" should be accepted with reservation. The fact that the tendons surrounded by polythene tubes had a better range of passive movement than the control tendons was natural and could have been anticipated; a biological union between the tendon and polythene was impossible and therefore peritendinous adhesions had nowhere to which to attach themselves. With reference to the poor function obtained with the control tendons it is to be noted that 20 of the 25 control tendons or 80% of the series had little or no benefit of functional activity. (Table 3).

| NO. OF CASES | PERIOD BETWEEN REMOVAL OF SPLINTAGE AND EXAMINATION (FUNCTIONAL ACTIVITY) |
|---|---|
| 15 | 0 Days |
| 5 | 2-9 Days |
| 5 | 15-71 Days |

Table 3. An analysis of the periods between removal of the immobilising splint and the final assessment.

No surgeon would attempt to assess the results of a tendon suture immediately after, or a few days following the removal of the immobilising splint. Given time and active movements, peritendinous adhesions can resolve to a certain extent and function can be greatly improved. An analysis of the five control tendons that were allowed an adequate period of functional activity exhibited "functional" ratings comparable to the polythene tendons. (Table 4).

| DOG NO. | PERIOD OF MOBILISATION (FUNCTIONAL ACTIVITY) | PERIOD OF IMMOBILISATION | FUNCTIONAL RATING | |
|---|---|---|---|---|
| | | | CONTROL | POLYTHENE |
| 48/286 | 15 Days | 29 Days | + | +++ |
| 48/233 | 18 Days | 23 Days | + | o |
| 48/81 | 19 Days | 28 Days | + | o |
| 48/68 | 54 Days | 14 Days | + | o |
| 48/246 | 71 Days | 8 Days | o | o |

Table 4. The functional ratings of the tendons that were allowed a reasonable or adequate period of functional activity. The last mentioned control tendon (Dog. No. 48/246) was immobilised for 8 days only, and the poor functional result readily accounted for.

Although strong healing of the polythene tendons was demonstrated, a serious objection to the method was the long period of immobilisation required, namely, forty days. Prolonged immobilisation of the digital joints readily leads to stiffness and their subsequent mobilisation presents a difficult problem.

# CHAPTER 4

## THE EXPERIMENT

When the idea of the use of a vein graft as a suitable substitute for a damaged tendon sheath was conceived, the fate of a transplanted vein had to be determined and thereafter the selection of a vein of suitable diameter to "ensheath" a tendon had to be considered. Having completed these preliminary investigations, a controlled experiment to assess the value of the procedure was essential. It soon became apparent that a controlled experiment in man would be almost impossible. Consequently the experiments were performed on monkeys, a species whose hand presented features structurally and functionally comparable to man.

The text of this chapter consists of a series of experiments relating to the above sequence of ideas and events.

### (I) THE FATE OF AUTOLOGOUS HUMAN VENOUS GRAFTS

The reasons for the contemplated use of autologous venous grafts, as a suitable tissue for the prevention of adhesions following tendon suture, were considered on Page 7. Before attempting the method it was essential to determine the changes in the venous transplant and the reaction of the tissues to its presence. The patency of the lumen, the state of preservation of the intimal endothelium, and the integrity of the elastic tissues were particularly investigated.

### THE METHOD

In four adult males who required a bilateral high saphenous vein ligation and resection for varicose veins, a half inch segment of the excised saphenous vein was transplanted into the subcutaneous tissues of the opposite thigh through a small skin incision at the completion of the first operation. Only veins that were macroscopically normal were transplanted. The procedure involved did not subject the patient to any undue trauma or risk, as the vein was placed in the line of incision required for the second operation. At the time of operation on the second limb, the intervals varying between 36 and 50 days, the transplanted venous grafts were removed and examined both macroscopically and microscopically. Detection of the sites of the grafts was facilitated by the presence of the small healed skin incisions. On exposing the subcutaneous tissues the venous transplants were recognised by palpation; they were firmer in consistency than the surrounding tissues.

## THE RESULTS

### THE MACROSCOPICAL APPEARANCES

In all four instances the venous transplants felt indurated and could not be dissected out with the ease with which a normal vein strips from its bed. On section evidence of a lumen was noted in two of the transplants. The lumina of the remaining two specimens were occluded with what appeared to be organising blood clot. The transplanted veins were then immersed in 10% formalin, embedded in wax and sectioned at 4 microns.

The pathological changes in the venous transplants can be more readily appreciated by comparison with a vein of normal histology. (Page 58).

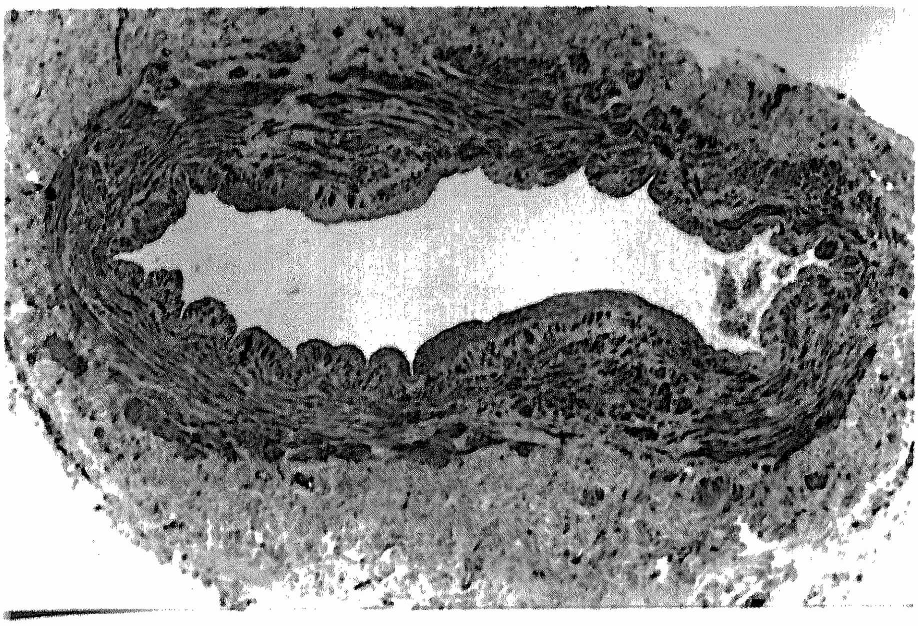

Fig. 30 Photomicrograph of a transverse section of a normal vein. (great saphenous)
Haematoxylin and Eosin X 40

Note 1. The endothelium of the tunica intima consisting of a single layer of flattened cells.
2. The well defined tunica media, consisting mainly of circular muscle fibres. In the bottom right hand corner of the photomicrograph, a few well defined longitudinal muscle bundles are seen extending into the adventitia.
3. The adventitia containing coarse irregular collagenous fibres.

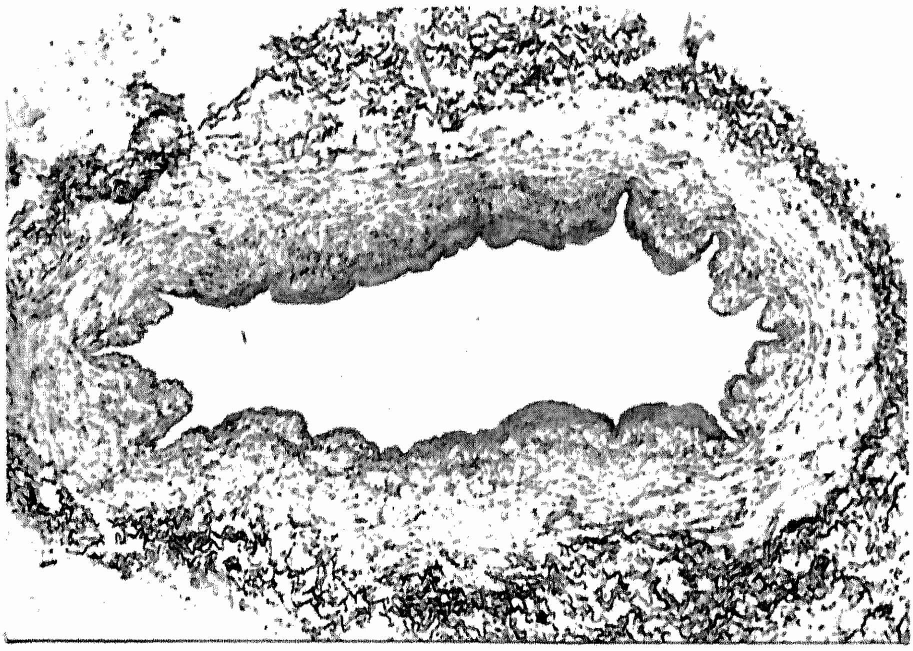

Fig. 31 Photomicrograph of the same specimen as Fig. 1 demonstrating the elastic fibres.
Weigert X 40

Note the well defined elastic networks in the tunica adventitia, and the thin tortuous subintimal elastic lamina.

## THE HISTOLOGY OF A NORMAL VEIN

Figs. 30 and 31 are photomicrographs of transverse sections of a normal great saphenous vein removed from the groin. The external diameter of the vein is 4 mm's., and it falls into the category of medium sized veins.

### THE LUMEN

The lumen is collapsed, irregular in shape and thrown into numerous folds, unlike the lumen of an artery of corresponding calibre, whose circular outline is usually well maintained.

### THE INTIMA

The endothelial lining of the tunica intima consists of a single layer of contiguous flattened cells. The subintimal layer is composed of a well developed connective tissue layer, containing a few fibroblasts and scattered, irregularly disposed, thin elastic fibres. A few muscle fibres which are on the whole longitudinally disposed, are present in the subintimal layer.

### THE TUNICA MEDIA

The tunica media in this specimen is well defined, consisting mainly of circular smooth muscle fibres separated by occasional longitudinal muscle fibres and a few fibroblasts. Thin elastic fibres are scattered throughout the tunica media and at the periphery of this layer, occasional well defined longitudinal muscle fibres are noted, which in parts extend into the adventitia.

### THE TUNICA ADVENTITIA

The tunica adventitia consists of loose connective tissue containing thick collagenous bundles which are mainly disposed longitudinally. Note the well defined elastic networks.

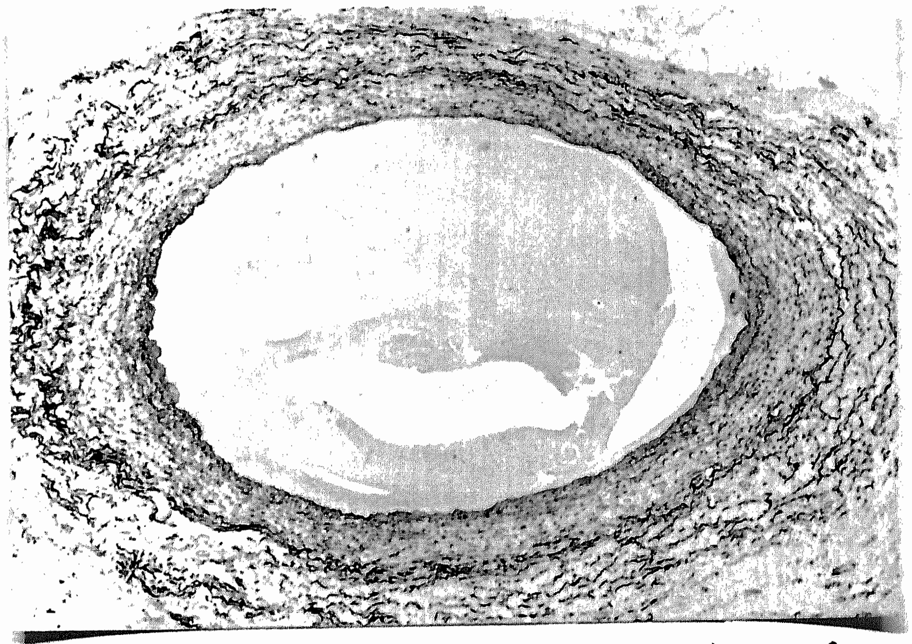

Fig. 32 Photomicrograph of a transverse section of venous transplant No. I
Haematoxylin and Eosin X 30

The lumen of the vein contains granulation tissue in which there are foci of recent and old haemorrhage. The endothelium of the lumen consists of a single layer of flattened cells. The muscle fibres of the tunica media have almost completely disappeared. Note the invasion of the tunica adventitia by numerous capillaries.

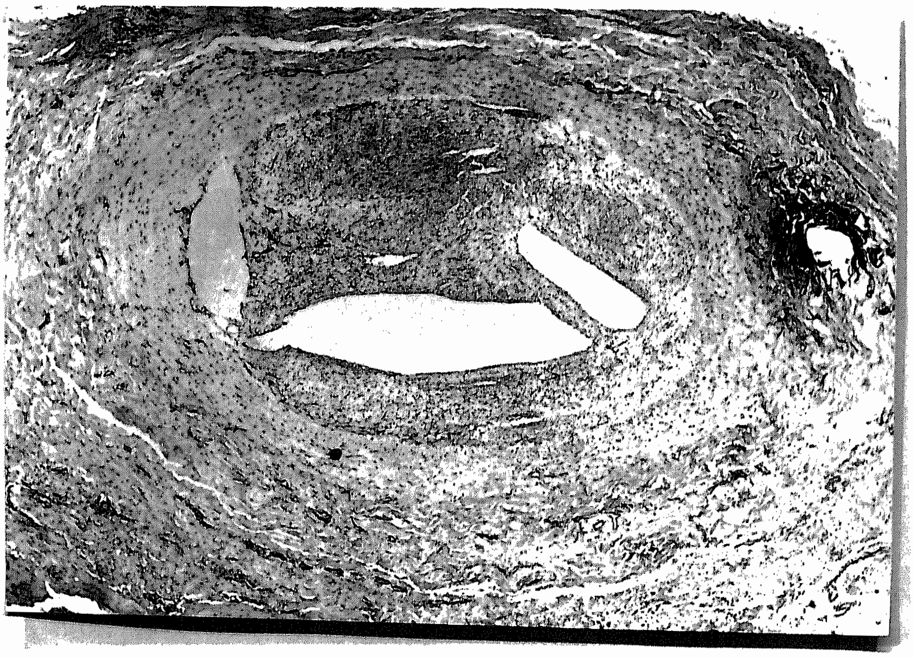

Fig. 33 Photomicrograph of a transverse section of venous transplant No. I demonstrating the elastic tissue.
Weigert X 30

Note the well defined and preserved subintimal elastic lamina, and the coarse elastic fibres of the tunica adventitia.

## THE HISTOLOGY OF THE VENOUS TRANSPLANTS

### VENOUS TRANSPLANT NO. I

Figs. 32 and 33 are photomicrographs of transverse sections of a great saphenous vein that had been transplanted for a period of 50 days.

### THE LUMEN

The lumen, partially obliterated, contains an irregularly shaped blood clot which is attached to the intima and in the process of organisation.

### THE INTIMA

The endothelium of the lumen of the vein, and that investing the blood clot is indistinguishable from normal intimal endothelium, consisting of a single layer of flattened cells. Granulation tissue, consisting of numerous fibroblasts and small round chronic inflammatory cells, has invaded the lumen. A well defined subendothelial elastic lamina is present (Fig. 33) continuous throughout its entire circumference, even where adjacent to the organising blood clot.

### THE TUNICA MEDIA

The tunica media is identifiable by the presence of a few scattered circular and longitudinal elastic fibres. Most of the muscle fibres have undergone degeneration and atrophy.

### THE ADVENTITIA

The adventitia is more vascular than normal, and contains numerous foci of foreign body reaction in which giant cells are present. The concentric coarse elastic fibres (Fig. 33) are well preserved, and difficult to distinguish from the normal.

### SUMMARY

The lumen has been partially obliterated by organising blood clot. Those portions of the lumen which are still intact, are lined by endothelium difficult to distinguish from the normal. The muscle fibres of the tunica media have largely disappeared. The elastic fibres are well preserved. The adventitia has been invaded by numerous small blood vessels, and contains foci of foreign body reaction.

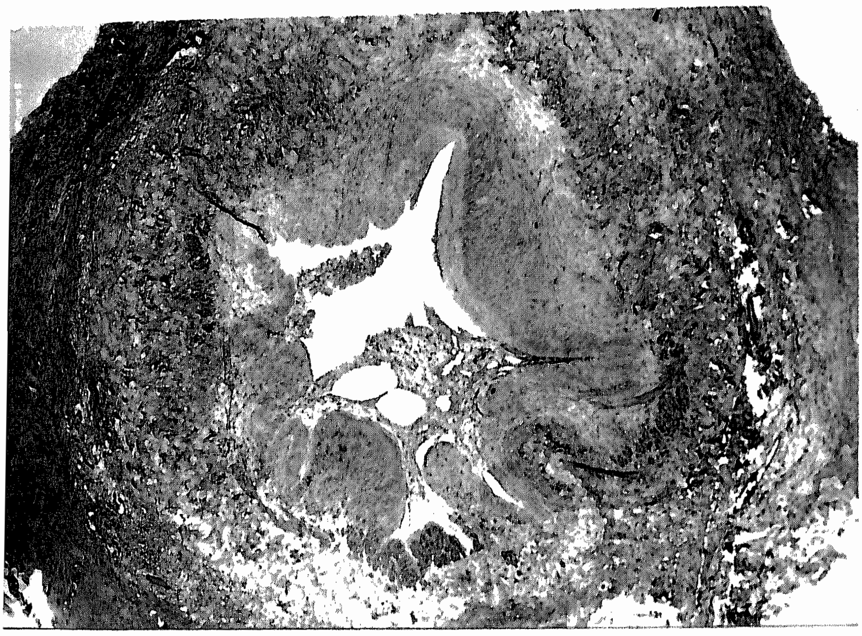

Fig. 34 Photomicrograph of a transverse section of venous transplant No. 2.

Mallory X 40

The lumen is partially filled with granulation tissue and contains large clefts lined by endothelium. The appearance is not unlike the histological features seen in thrombi undergoing recanalisation. Note the circular muscle fibres of the tunica media.

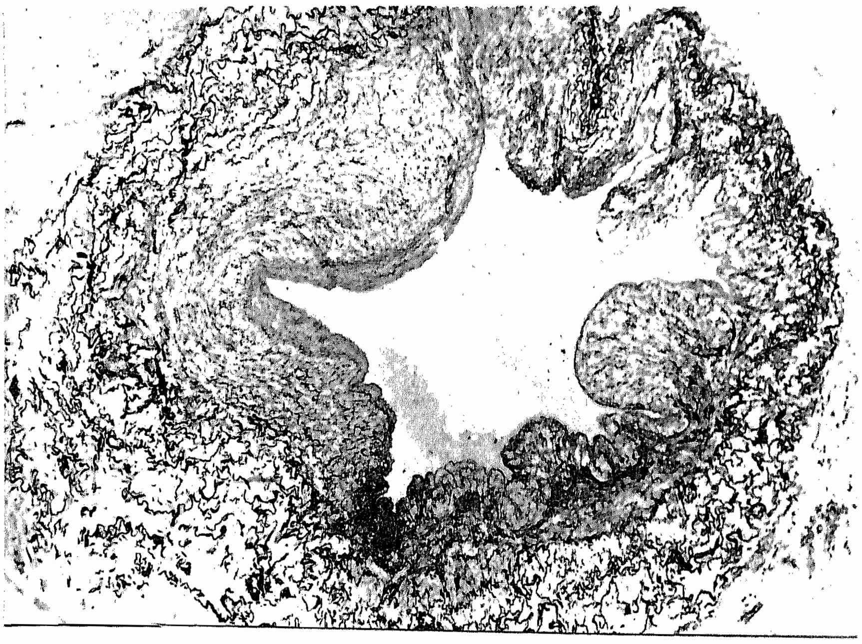

Fig. 35 Photomicrograph of a transverse section of venous transplant No. 2 to demonstrate the elastic tissue.

Weigert X 40

Note the well defined and preserved elastic fibres in the adventitia.

## VENOUS TRANSPLANT NO. 2

Figs. 34 and 35 are photomicrographs of a venous graft transplanted for a period of 36 days.

### THE LUMEN

The lumen is thrown into folds giving it a stellate appearance. Granulation tissue consisting of numerous fibroblasts, small round cells and thin walled capillaries bridges the lumen. A well defined endothelial layer, indistinguishable from the normal endothelium of the intima is present on the surface of the granulation tissue. The subintimal layer is well defined and hypertrophied and contains an ill defined elastic lamina. No muscle fibres are evident in this stratum.

### THE TUNICA MEDIA

With the exception of a third of its circumference, the muscle fibres of the tunica media are well defined. In parts the muscle fibres are histologically normal, but there are numerous-areas of cell degeneration as evidenced by disintegration of the nuclei and cell membranes.

### THE ADVENTITIA

The adventitia contains a well defined circular network of coarse elastic fibres in which numerous capillaries are present. Several foci of foreign body reaction are present in which giant cells are noted.

### SUMMARY

The lumen although encroached upon by granulation tissue is lined by endothelium. The elastic laminae are preserved, and the muscle fibres of the tunica media with the exception of a portion of the circumference are apparently normal. The adventitia is more vascular than normal and contains foci of small round cells and giant cells, indicating a foreign body chronic inflammatory reaction.

Fig. 36 Photomicrograph of a transverse section of venous transplant No. 3.
Haematoxylin and Eosin X 40

The lumen of the vein is almost completely obliterated by granulation tissue. No obvious muscle fibres are noted in the tunica media. Note the increased vascularity of the tunica adventitia.

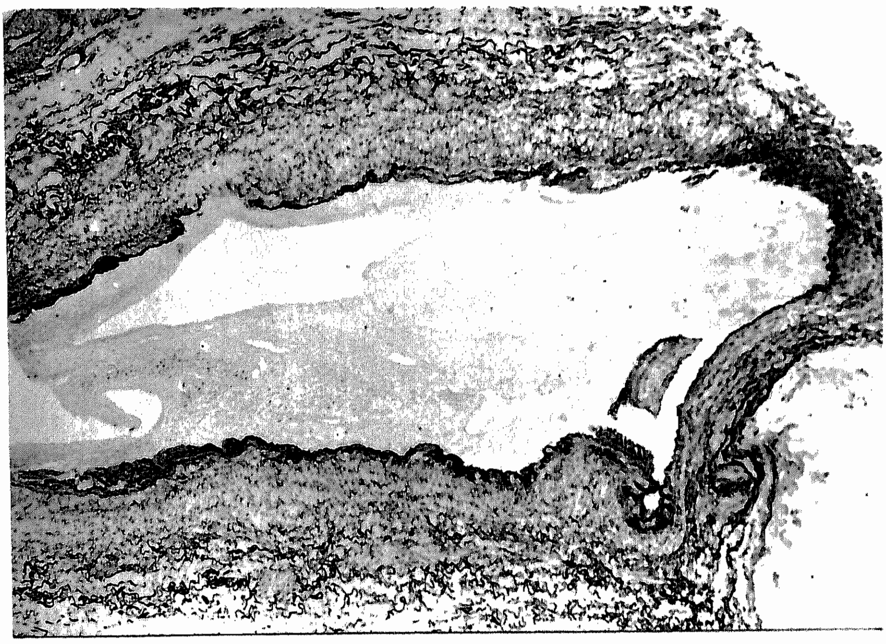

Fig. 37 Photomicrograph of a transverse section of venous graft No. 3 to demonstrate the elastic tissue.
Weigert X 40

Note the preservation of the subintimal elastic laminae and the coarse elastic fibres of the tunica adventitia.

## VENOUS TRANSPLANT NO. 3

Figs. 36 and 37 are photomicrographs of transverse sections of a venous graft transplanted for a period of 42 days.

### THE LUMEN

The lumen is almost completely filled with granulation tissue. The intimal surface of that portion of the lumen which is free of granulation tissue is lined by endothelial cells.

### THE TUNICA INTIMA

A well defined subendothelial elastic lamina is present and intact. (Fig. 37).

### TUNICA MEDIA

On the whole the muscle fibres of the tunica media have been replaced by granulation tissue.

### TUNICA ADVENTITIA

The tunica adventitia contains well defined coarse elastic networks (Fig. 37), marked fibrous tissue infiltration, and foci of chronic inflammatory reaction.

### SUMMARY

Most of the lumen has been obliterated by granulation tissue. The elastic laminae are well preserved. The muscle fibres of the tunica media have been largely replaced by granulation tissue. Foci of chronic inflammation are present in the adventitia.

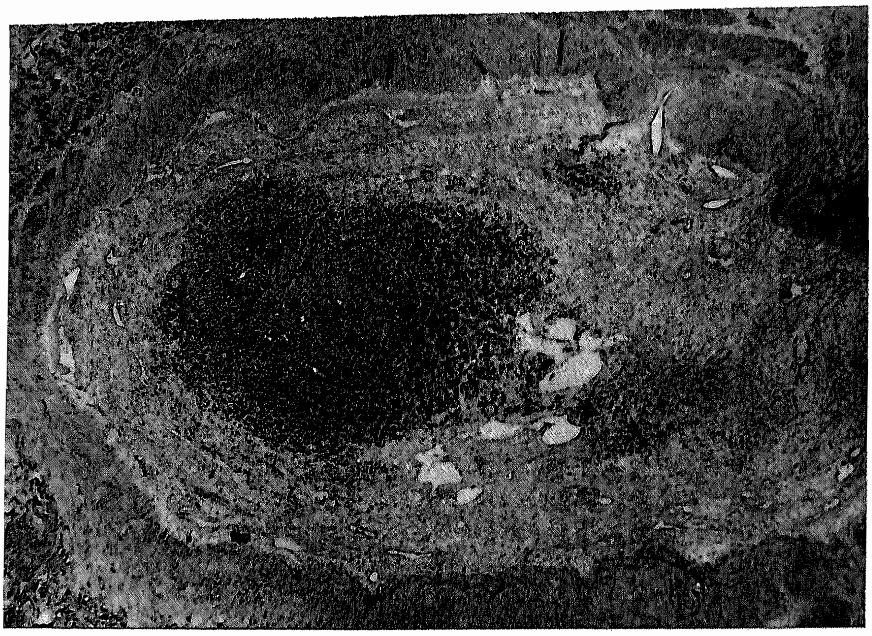

Fig. 38 Photomicrograph of a transverse section of venous transplant No. 4

Mallory X 45

The lumen of the vein has been almost entirely occluded by granulation tissue containing recent haemorrhage. Numerous cleft-like spaces lined by endothelium are noted. The muscle fibres of the tunica media have largely disappeared, but occasional muscle fibres are to be seen, particularly at the top and bottom right hand corners of the photomicrograph.

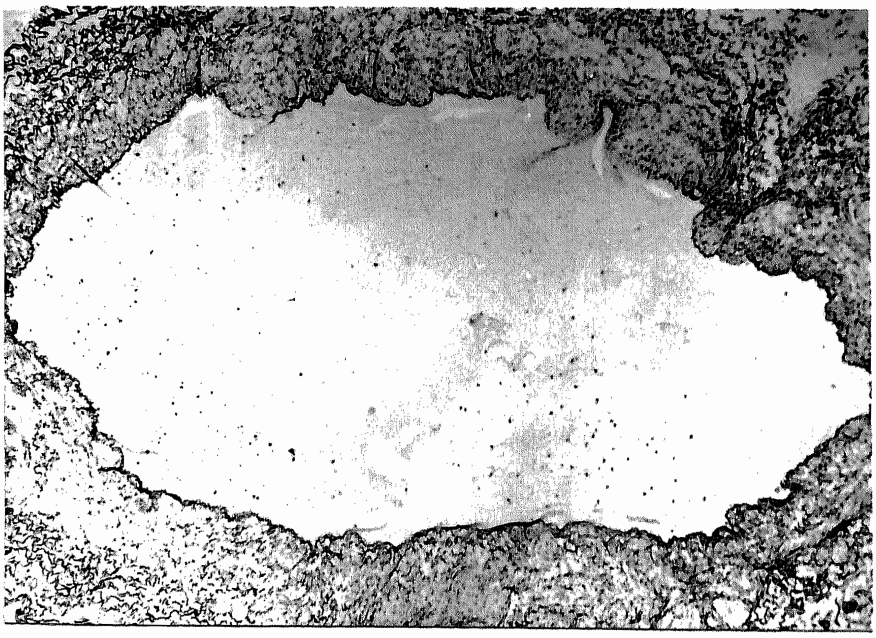

Fig. 39 Photomicrograph of transverse section of venous transplant No. 4 to demonstrate the elastic fibres.

Weigert X 45

Note the well defined subintimal elastic lamina and the coarse elastic fibres in the tunica adventitia.

Fig. 40 Photomicrograph of a longitudinal section of venous transplant No. 4

Mallory X 40

Note the presence of granulation tissue in the lumen. It contains foci of recent haemorrhage. Muscle fasiculae are evident in the tunica media.

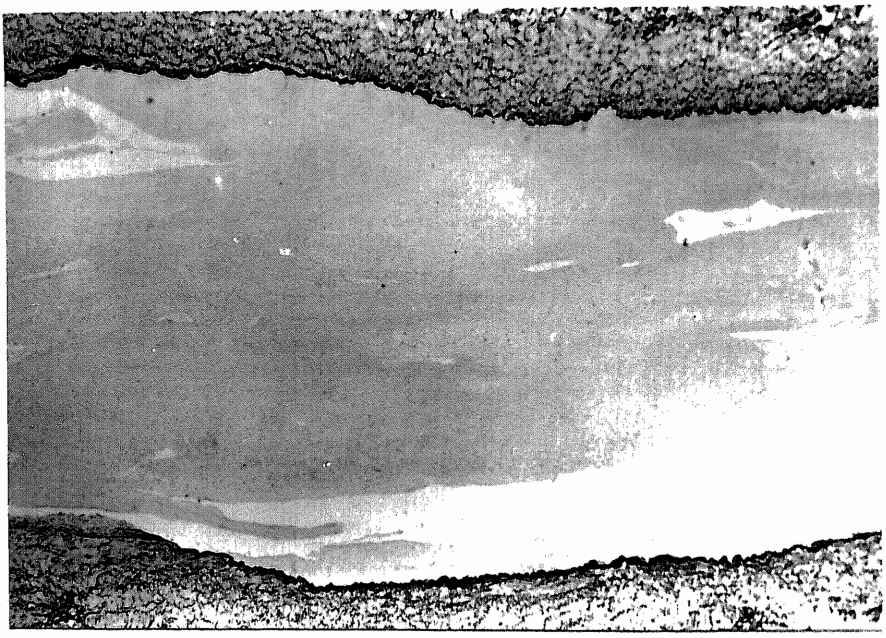

Fig. 41 Photomicrograph of a longitudinal section of venous transplant No. 4, demonstrating the elastic tissue.

Weigert X 40

Note the well preserved subendothelial elastic lamina and the coarse elastic fibres of the tunica adventitia.

## VENOUS TRANSPLANT NO. 4

Figs. 38, 39, 40 and 41, are photomicrographs of sections of a great saphenous vein, transplanted for a period of 46 days.

This specimen was bisected. The one half was sectioned transversely and the other longitudinally.

### (A) TRANSVERSE SECTIONS (Figs. 38 and 39)

### THE LUMEN

The lumen has been almost entirely obliterated by granulation tissue containing foci of recent haemorrhage. There are a few cleft-like spaces in the granulation tissue, lined by a single layer of endothelial cells. One of these spaces contains fibrin.

### THE INTIMA

The subendothelial stratum is hypertrophied and its elastic lamina well preserved. (Fig. 39).

### THE TUNICA MEDIA

Most of the muscle fibres of the media have been replaced by granulation tissue. Those remaining have normal histological features.

### THE TUNICA ADVENTITIA

The tunica adventitia has been invaded by fibrous tissue and numerous small blood vessels. There are foci of small round cells with foreign body giant cells. The elastic fibres are well preserved.

### (B) LONGITUDINAL SECTIONS (Figs. 40 and 41)

### THE LUMEN

Most of the lumen of the vein is filled by granulation tissue which is attached to the intima. The remaining portion is still patent and its surface has an endothelial lining. Foci of recent haemorrhage are present in the granulation tissue.

### THE TUNICA INTIMA

The tunica intima has a well defined subendothelial elastic network continuous in its whole extent. The connective tissue of this stratum is increased in quantity.

## THE TUNICA MEDIA

The muscle fibres of the tunica media are more obvious in the longitudinal sections than in the transverse sections.

## THE TUNICA ADVENTITIA

Numerous capillaries and small foci of round cells with foreign body giant cells have invaded the adventitia. The elastic fibres of the adventitia are well preserved.

## SUMMARY

The elastic laminae are well preserved. The muscle fibres of the tunica media are replaced in part by granulation tissue. In the longitudinal sections the endothelial lining of the intima is intact on the one aspect of the lumen.

## CONCLUSIONS

The histological findings revealed that the venous transplants had survived periods of time of up to fifty days. This statement is based on the observation that the grafts had become vascularised, a fact conclusively supported by the presence of infiltrating blood vessels in the tunica adventitia, and the presence of capillaries and foci of recent haemorrhage in the granulation tissue which had invaded the lumina.

The elastic laminae were well preserved, but the muscle fibres, although apparently normal in parts, showed evidence of commencing atrophy, degeneration and replacement by granulation tissue, the degree of replacement varying according to the duration of transplantation. The degenerative changes in the muscle fibres were anticipated, and coincide with pathological changes in muscle tissue elsewhere, where denervation or disuse leads to atrophy.

Evidence of a lumen was noted in all the venous transplants, in one (specimen No. 2) almost intact, but in the rest only partially. In each instance an endothelial lining was noted, which was difficult to distinguish from normal intimal

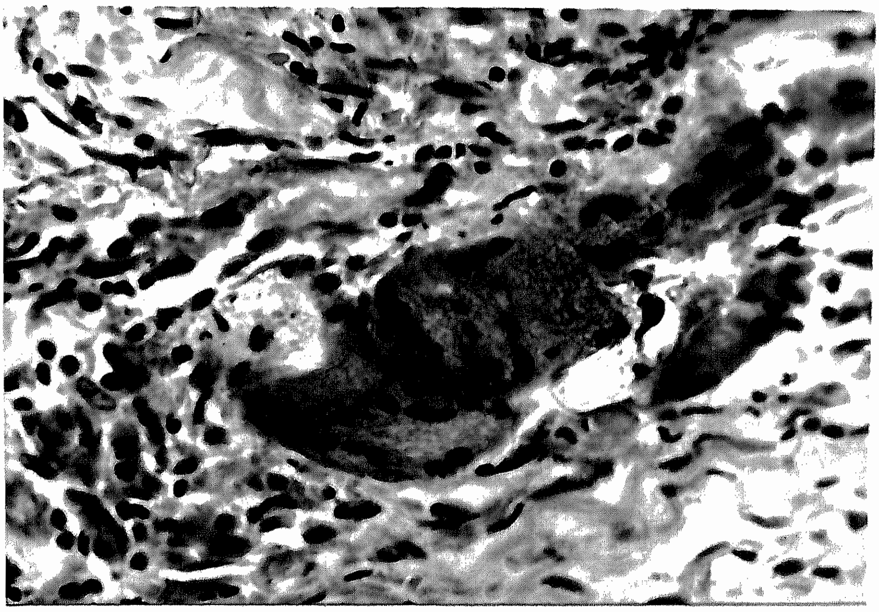

Fig. 42 Photomicrograph of a focus of foreign body tissue reaction in the tunica adventitia.
Haematoxylin and Eosin X 450

Note the foreign body giant cells and the numerous small darkly stained chronic inflammatory cells. This reaction was noted in the tunica adventitia of all the venous transplants.

endothelium.

The origin and purpose of the granulation tissue within the lumina is open to speculation. It is conceivable that its presence was the result of organisation of blood clot present at the time of transplantation since the venous grafts were not irrigated prior to transplantation. On the other hand it is highly probable that the presence of the intraluminal granulation tissue was nature's attempt to obliterate dead space, and that had the venous transplants been allowed to remain in situ for longer periods, complete obliteration of the lumina would have occurred.

Had biologically inert rods been inserted into the lumina of the veins it is certain that they would have maintained their patency. The presence of numerous foci of foreign body reaction in the tunica adventitia is difficult to explain. (Fig. 42). No sutures or other materials capable of causing tissue irritation were inserted at the time of transplantation.

The conclusion that the grafts survived must be made with certain reservations. Occasionally a biopsy may fail to distinguish between survival of a transplant and creeping replacement by host tissue. (Woodruff 1952). Creeping substitution often occurs with bone grafts and blood vessels transplanted in continuity. In the case of the venous transplants, this occurrence was highly improbable because the general architecture was so well preserved. It is inconceivable that muscle and elastic tissue derived from surrounding tissues could have invaded the transplants and orientated itself to mimic the specialised structure of a vein. However, the possibility exists that with the further passage of time the venous grafts may have become completely replaced by fibrous tissue. Replacement would not necessarily have been detrimental, for the graft when placed around a tendon might have provided an effective scaffolding for the growth of synovial cells.

## (2) THE SELECTION OF A SUITABLE VEIN

In order to select a vein of suitable diameter to "ensheath" a sutured tendon, the diameters of the digital flexor tendons had to be determined.

### THE METHOD

In five adult cadavers, the long digital flexor tendons were exposed, and their widest diameters measured at three different levels : (a) at the wrist, (b) at the metacarpophalangeal joints and (c) at the interphalangeal joints of the remaining digits. In all twentyfive tendons were measured at three levels. Table 5 is a record of the findings.

| HAND | LEVEL | MAXIMUM DIAMETER OF TENDONS IN MM'S | | | | |
|---|---|---|---|---|---|---|
| | | THUMB | INDEX | MIDDLE | RING | LITTLE |
| 1 | WRIST | 3.5 | 3.4 | 4.1 | 3.3 | 2.7 |
| | M.P. JOINT | 3.1 | 3.6 | 3.9 | 3.4 | 2.9 |
| | P.I. JOINT | 3.2 | 3.3 | 3.9 | 3.5 | 3.0 |
| 2 | WRIST | 3.0 | 2.9 | 3.9 | 3.7 | 3.5 |
| | M.P. JOINT | 2.9 | 3.3 | 3.6 | 3.5 | 3.3 |
| | P.I. JOINT | 3.6 | 3.6 | 4.2 | 4.1 | 3.8 |
| 3 | WRIST | 4.0 | 3.9 | 4.1 | 3.7 | 3.8 |
| | M.P. JOINT | 3.8 | 3.6 | 4.1 | 4.2 | 4.1 |
| | P.I. JOINT | 3.7 | 3.9 | 3.8 | 3.9 | 4.0 |
| 4 | WRIST | 3.4 | 4.0 | 4.5 | 4.5 | 2.8 |
| | M.P. JOINT | 3.8 | 3.5 | 4.4 | 4.0 | 3.5 |
| | P.I. JOINT | 3.0 | 3.1 | 4.8 | 3.4 | 2.2 |
| 5 | WRIST | 3.3 | 3.4 | 4.0 | 3.7 | 2.9 |
| | M.P. JOINT | 2.8 | 3.3 | 3.8 | 3.5 | 2.8 |
| | P.I. JOINT | 3.1 | 3.2 | 3.9 | 3.4 | 2.7 |

Table 5. The maximum diameters of the long digital flexor tendons.
Key to Table:- M.P. Joint = Metacarpophalangeal joint
P.I. Joint = Proximal interphalangeal joint

Note that the widest tendon diameter encountered was 4.8

mm's., and the smallest diameter 2.2 mm's.

The flexor digitorum profundus tendon of the middle finger had the widest diameter, whereas the flexor digitorum profundus of the little finger, had the smallest diameter. At the wrist the flexor tendons were almost circular on cross section but approximately half an inch proximal to the metacarpophalangeal joints the flexor digitorum profundus tendons of digits 2, 3, 4 and 5 assumed an oval shape. The long flexor tendon of the thumb however, remained more or less circular throughout its whole length.

Having determined the variations in diameter of the digital flexor tendons, veins of adequate width had to be selected.

## THE METHOD

The great saphenous vein was exposed through a longitudinal incision above the medial malleolus in ten adult cadavers. The internal diameters were measured but on the whole they were found to be of inadequate dimensions.

Attention was then directed to the great saphenous vein in the groin. The measurements of the internal diameter of the great saphenous vein were made on fresh specimens, where one had ample opportunity to do so following completion of the Trendelenburg operation for varicose veins. The diameters of the great saphenous vein are represented in Table 6.

| PATIENT'S NO. | GREAT SAPHENOUS VEIN AT THE GROIN | DIAMETER OF LUMEN IN MM |
|---|---|---|
| 1. 259/VE | Left | 3 |
| 2. 215/VB | Right | 3.5 |
| 3. 13216 (25) | Right | 4.0 |
| 4. 439/VB | Right | 4.0 |
| 5. 34690 | Left | 7.0 * |
| 6. 426/VS | Left | 2.5 |
| 7. 15156 (25) | Left | 4.5 |
| 8. 44/VB | Right | 3.0 |
| 9. 246/VB | Right | 3.5 |
| 10. 239/VB | Left | 2.5 |

Table 6. The diameters of the great saphenous vein at the groin. *Specimen varicose.

Although the smallest diameter recorded was 2.5 mm. a glass cannula of diameter 5 mm. could be inserted through the lumen of each vein without difficulty, thus demonstrating the distensible nature of the vein.

## CONCLUSIONS

The results of these two investigations showed that a segment of great saphenous vein removed from the groin was of adequate dimensions to "sheath" the average digital flexor tendon.

Furthermore, the excision of a segment of the great saphenous vein from the groin appeared to have additional advantages in that the small oblique incision required for its removal would be inconspicuous, would heal well, and would be of adequate length to allow of the excision of at least a two inch segment of vein. A longer segment of vein, if multiple tendon repairs were required, could readily be obtained by vein stripping through two small transverse skin incisions. Segments of vein up to sixteen inches in length have been removed by this method.

Having established that a transplanted venous graft could survive, and retain its elastic content and endothelial lining, the next step in the experiment was to utilise this tissue in the repair of tendons. After careful consideration, however, it was decided not to attempt the method in the human, before satisfactory experiments had been performed in animals. The following reasons were responsible for this decision:

1. To have attempted this method in humans would have been morally wrong. In view of the fact that no reference could be found in the literature indicating that this method had been attempted in man, more harm than good may have resulted.
2. The most relevant factor to be established, the reproduction of a tendon sheath, could only have been determined by

histological section of a portion of tendon. The opportunity to perform a biopsy in man would have been remote.

3. A controlled experiment in man would have presented insurmountable obstacles and, therefore, the functional results difficult or impossible to assess.

The animals available for purposes of experimentation were the dog, rabbit or monkey. The monkey was chosen as the most suitable animal and the reasons for its choice will be discussed in the following section.

## (3) A STUDY OF THE HAND OF CERCOPITHECUS AETHIOPS (BLUE VERVET MONKEY)

A review of the literature on experimental tendon surgery revealed that most of the work had been performed on dogs or rabbits, animals anthropologically far removed from man. Furthermore, in the majority of instances the investigations were carried out on tendons in paratenon, and not in sheath formation. The dynamics of tendon action in sheath formation is a highly specialised one and following injury presents a difficult problem in treatment, unlike tendons in paratenon, in which function is relatively easily restored. As far as can be ascertained Gonzalez (1951) was the first to publish a report on experimental work involving the digital flexor mechanism. The animals he used however, were dogs, a species whose digital flexor mechanism subserves locomotion only and not prehension.

### REASONS FOR THE CHOICE OF THE MONKEY

The hands of the various Primates, including man, are very similar, and for the purposes of this experiment the monkey was considered ideal, having in common with man the highly developed function of prehension. Apart from man, this function is found only in Primates.

Frederick Wood Jones (1944) stated that "from a study of the human hand we cannot fail to have been struck with the fact that when we look for remarkable specialisations, for anatomical perfections, or wonderful human adaptations as distinguishing our hands from the hands of monkeys and anthropoid apes our search is rather a vain one. We shall look in vain if we seek for movements that a man can do and a monkey cannot, but we shall find much, if we look for purposive actions that a man does and a monkey does not. What we are admiring in the multitude of actions of the useful human hand is the human cerebral perfection, not the bones, muscles and joints that carry out the complex volitions". Beck (1925) on the other hand stated however, that "a comparative study of the

Fig. 43 Palmar surface of the left hand of C. Aethiops.

Note the typical simian proportions of the digits, 3 ⟩ 4 ⟩ 2 ⟩ 5 ⟩ 1. The diminutive thumb is conspicuous.

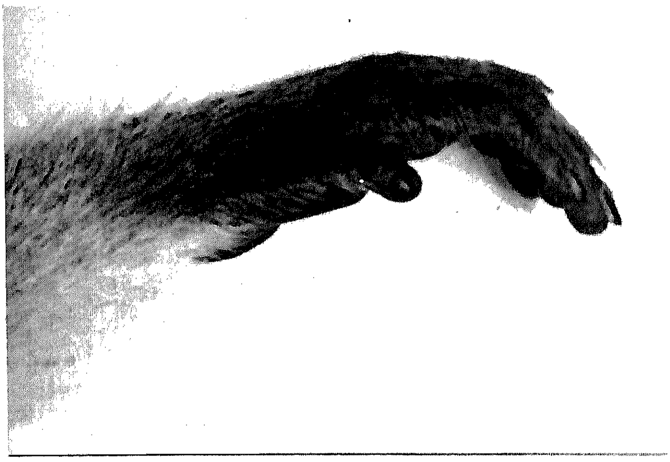

Fig. 44 Radial view of the left hand of C. Aethiops.

The hand is in the position of rest. Note that all the fingers are flexed to approximately the same degree. In the human hand, on adopting the position of test the little, ring, and middle fingers are bent towards the palm more markedly than the index finger which lags behind in the degree of flexion - evidence of the independence of action of the index finger. Note the distribution of hair.

human hand and the corresponding extremity of the highest developed animal shows great differences of structure and form!"

Confronted with these two divergent views, it was deemed necessary to make a personal study of the monkey's hand to gain first-hand information of the anatomy and function before proceeding with the experiment.

The anatomical dissections and subsequent experiments were performed on the hands of monkeys, belonging to the genus Cercopithecus Aethiops, commonly known in South Africa as the Blue Vervet Monkey. These animals are generally distributed throughout South-East Africa. Along the Natal Coast, they make frequent raids upon cultivated gardens and fields of grain, often causing considerable damage and displaying remarkably little fear of man. Although frequently adopted as a pet, the Blue Vervet is by no means docile or easily tamed, but is usually bad tempered, treacherous and savage, displaying its teeth and using them to good effect on the least provocation. The animal tolerates captivity well and is admirably suited to experimental research.

## A STUDY OF THE HAND OF C. AETHIOPS.

Although mainly concerned with the anatomy and function of the digital flexor mechanism, numerous observations of interest from the point of view of comparative anatomy were noted and are, therefore, being recorded.

## THE FORM, SHAPE AND INTEGUMENT OF THE HAND.

Figs. 43 and 44 are photographs of the palmar and radial aspects of the hand an adult monkey. Unlike man whose thumb is distinctive in its degree of specialisation, strength, opposability? opposition and size, the thumb of the monkey is small. In the human hand the pollical index, or percentage of length of thumb to that of the middle finger is about 55% as compared to 33% in C. Aethiops. The thumb of the monkey and of the ape is the smallest and least opposable of that found among all the primates. (Wood Jones).

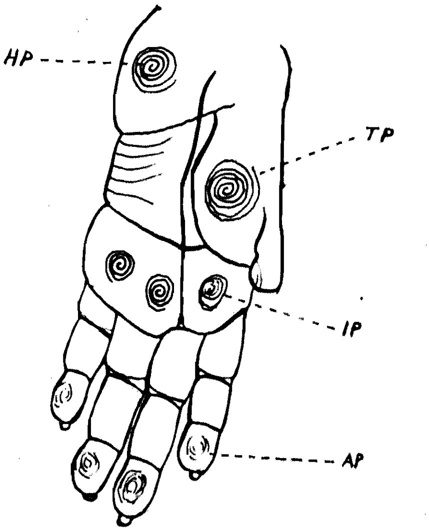

Fig. 45 The volar surface of the hand to illustrate the palmar pads and creases. (C. Aethiops).

Note that the distal transverse palmar crease which in man ends in the 2nd interdigital space, runs completely across the palm. The proximal longitudinal crease is due to the curvature of the metacarpal arch. The nails are narrower and more curved than the nails of the human.

(HP) Hypothenar pad.
(TP) Thenar pad.
(IP) Interdigital pad.
(AP) Apical pad.

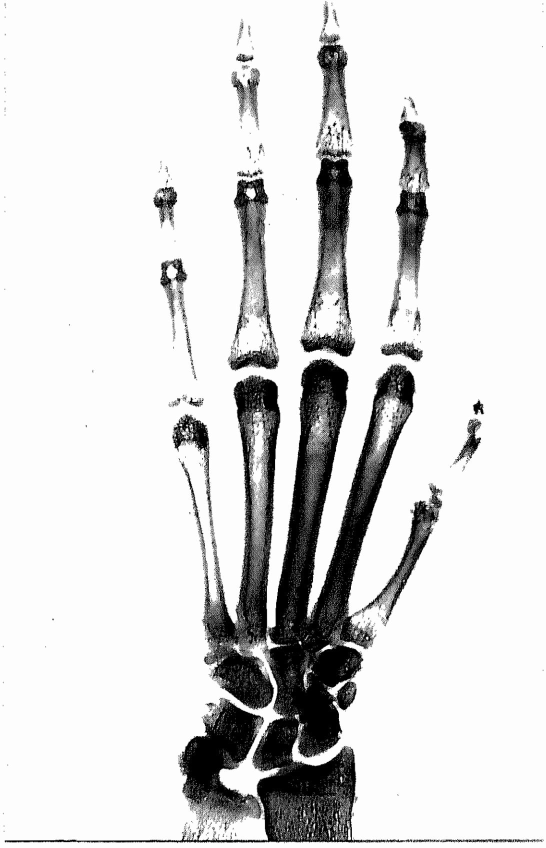

Fig. 46 Antero-posterior radiograph of the bones of the hand. (C. Aethiops).

Refer to Fig. 47 for key to the carpal bones. Note the presence of the os centrale and the sesamoid lateral to it. The digital, phalangeal and metacarpal formulae are similar to the basic pattern found in man.

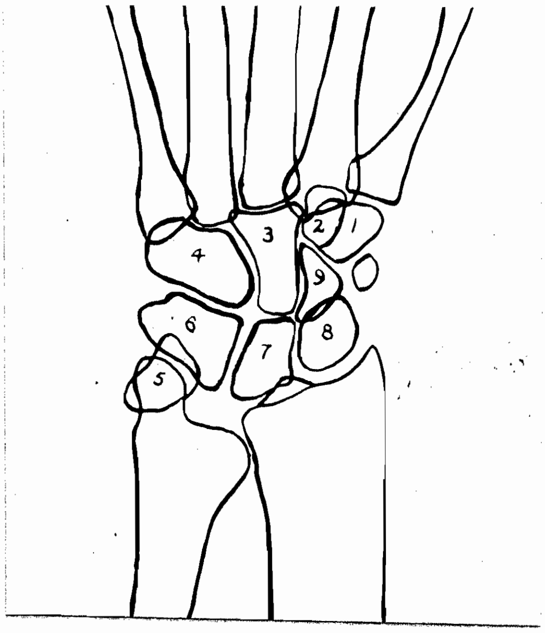

Fig. 47 Key to carpal bones. (C. Aethiops).

(1) Multangular major. (2) Multangular minor. (3) Capitate. (4) Hamate.
(5) Pisiform. (6) Triquetrum.
(7) Lunate. (8) Scaphoid.
(9) Os centrale.

The ossicle not enumerated is a sesamoid in the tendon of the abductor pollicis longus. Note the prominent ulnar styloid and the superimposition of the multangular major on the multangular minor.

The digital, metacarpophalangeal and phalangeal formulae are essentially the same as the basic pattern found in man, namely $3 > 4 > 2 > 5 > 1$, $2 > 3 > 4 > 5 > 1$, and ~~$2 > 3 > 3 > 3 > 3$~~ 2, 3, 3, 3, 3 respectively. (Fig. ~~48~~ 46). The length of the hand relative to that of the arm, is greater in ~~the monkey~~ C. aethiops than in man.

## THE INTEGUMENT

Finger prints or papillary ridges are present and are similar to those found in man, differing only in disposition and complexity. Their presence indicates the use of the hand as a sense organ. The well developed pads over the volar aspects of the distal phalanges, metacarpal heads and base of the palm are evidence of the locomotor activities of the hand. (Fig. 45).

The conspicuous crease patterns in the palm are of interest. (Fig. 45). The distal transverse palmar crease runs completely across the palm, allowing only for flexion of the fingers as a whole. In man the distal transverse crease begins at the ulnar border of the hand, passes obliquely to the cleft between the index and middle fingers, and does not cross the palm at the base of the index finger. The termination of the distal transverse crease in the second interdigital cleft is a human peculiarity. It signifies the specialisation of the index finger as manifested by the independence of its movements, and distinction as a pointing or scratching digit. The distal palmar crease in man, is for flexion against the thumb of the medial three fingers, and the proximal palmar crease for the lateral three. Thus in the human hand there is a differential action between the two sides of the hand. (Wood Jones).

The monkey's nails are relatively narrower and more curved, in both cases than in man, and the interdigital webs less (well conspicuous? developed.)

## THE BONES OF THE HAND

### (a) THE CARPAL BONES:

The carpus consists of nine carpal bones and a sesamoid.

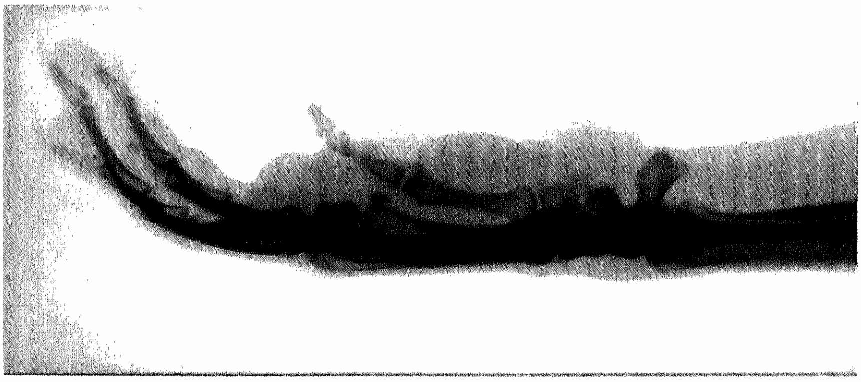

Fig. 48 Lateral radiograph of the bones of the hand (C. Aethiops).

Note the very prominent and conspicuous pisiform and tubercle of the scaphoid. Compare with the human hand Fig. 49.

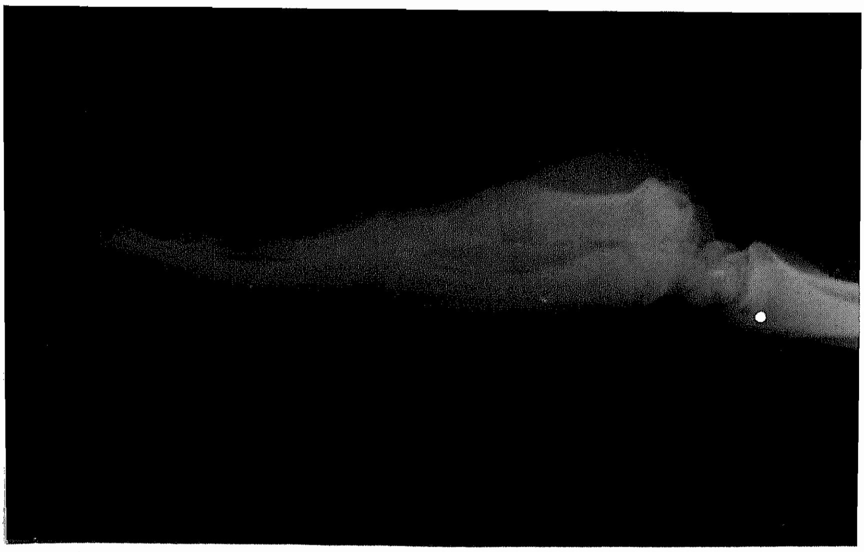

Fig. 49 Lateral radiograph of the bones of the human hand.

The pisiform of the human hand in comparison with the pisiform of the monkey (Fig. 48) is rudimentary.

(Figs. 46 and 47). As in the human there is a proximal and distal row of four bones, but there is in addition, on the radial side between the two rows, an intermediate central bone – the os centrale. The proximal row consists of the navicular, lunate, triquetrum, in order from the radial to the ulnar side. The pisiform stands out as the most conspicuous carpal bone and lies anterior to the triquetrum. (Fig. 48). This bone and the tubercle of the scaphoid project for great muscle leverage in locomotion. In man the pisiform is rudimentary. (Fig. 49).

The distal row of the carpus consists of the hamate on the ulnar side, followed by the capitate, multangular major and minor. This row is curved anteriorly at its radial side, so that the multangular trapezium major is anterior, rather than lateral to the multangular trapezoid minor, as is the case in the human hand.

The os centrale is situated so that it articulates largely with the navicular of the proximal row, and with the capitate and the two multangulars of the distal row. It has a small articulation with the lunate. The os centrale, though present in the embryo of most mammals, fuses with the scaphoid before birth. In man it appears in the sixth week and fuses in the eighth, thus losing its individuality. Rarely it may persist in the human carpus (Wood Jones 1948).

Although the os centrale is truly a central carpal bone in reptiles and in some mammals, it tends to migrate towards the preaxial border of the carpus in many species, especially the Primates. Wood Jones states that the human scaphoid is a compound bone, being composed of the primitive scaphoid in its proximal part and the preaxially displaced os centrale in its distal part, and this incorporation is an expression of the specialisation of the functions of the human index finger being necessary for stability at the base of this important digit.

Omit.

The sesamoid on the antero-lateral surface of the

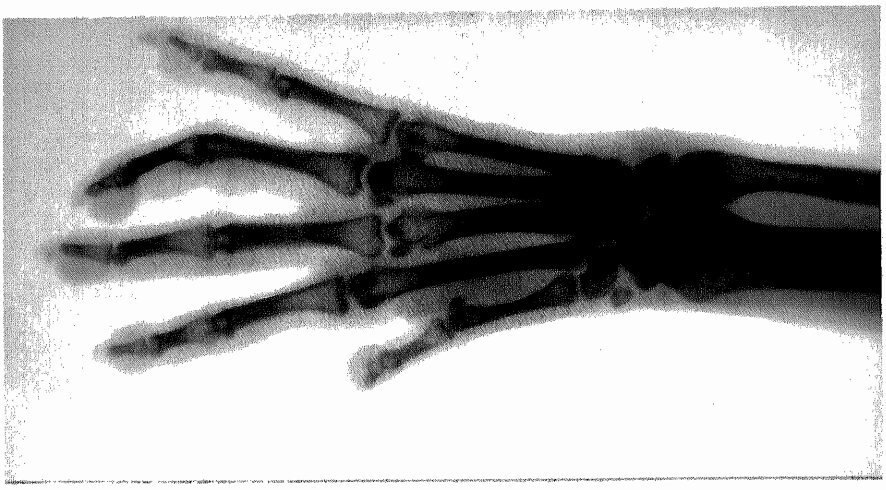

Fig. 50 Antero-posterior radiograph of the hand illustrating the numerous sesamoids. (C. Aethiops).

Note the presence of a pair of sesamoids at each of the metacarpophalangeal joints. Compare with Fig. 51 the sesamoids of the human hand.

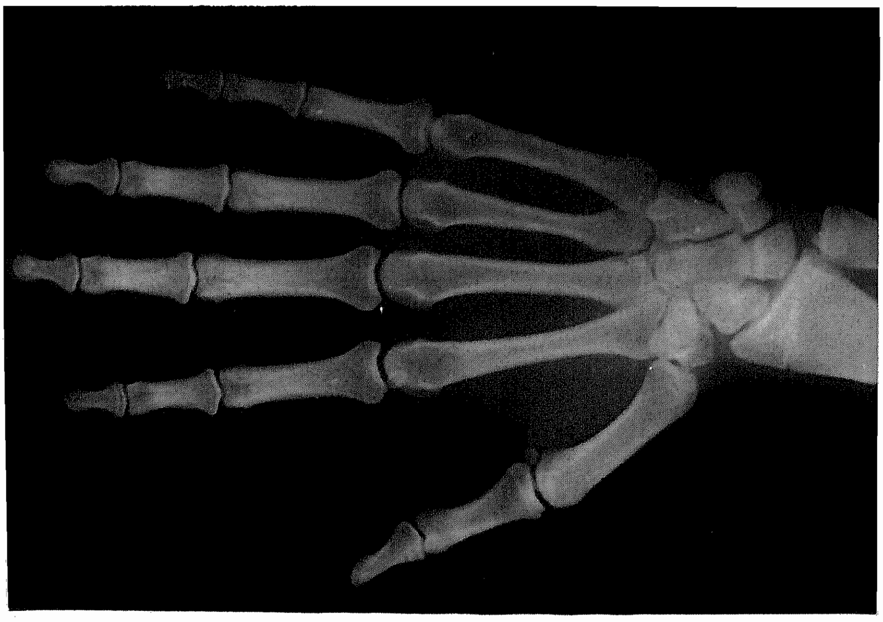

Fig. 51 Antero-posterior radiograph of the humand hand.

The presence of a pair of sesamoids at each of the metacarpophalangeal joints as found in the monkey, is not duplicated in man. In this X-Ray of the human hand they occur singly at the metacarpophalangeal joints of the thumb, index and little fingers.

Fig. 52 The digital flexor tendons. (C. Aethiops).

Note the disposition of the flexor pollicis longus tendon. It is thinner than the profundus tendons to the remaining digits and arises from the common profundus muscle. Along its course to the distal phalanx of the thumb it courses between the flexor digitorum profundus and sublimus tendons of the index finger. The remaining extrinsic digital flexors are essentially the same as those found in man. Note the well developed lumbrical muscles.

Fig. 53 The digital extensor tendons. (C. Aethiops).

Note the extensores proprii of digits, 3, 4 and 5. The extensor proprius indicus of digit 4 is not obvious in this photograph since it blends with the under surface of the tendon of the extensor digitorum communis of the same finger.

trapezium.

multangular major is associated with the tendon of the abductor pollicis longus.

## (b) THE METACARPUS AND PHALANGES

The metacarpal bones and phalanges warrant no special description, other than to state that they have the same general pattern as found in man.

## (c) THE SESAMOID BONES

Two sesamoids, a medial and a lateral, varying in size are present at each of the metacarpophalangeal joints, giving the impression of dumb-bells (Fig. 50). They lie transversely to the axis of the joint, the groove between them acting as a pulley for the flexor tendons. In man this degree of perfection is not attained and their number is inconstant, but in practically every case the sesamoids exist at the flexor surface of the metacarpophalangeal joints of the thumb (Fig. 51). Two similar bones or only the radial member of the pair, are not infrequently present on the flexor surface of the interphalangeal joint of the thumb. Occasionally a single sesamoid may be present on the ulnar side of the fifth metacarpophalangeal joint or on the radial side of the second metacarpophalangeal joint. Sesamoids in relation to other metacarpophalangeal joints are a distinct rarity in the human hand.

## THE MUSCLES OF THE HAND OF C. AETHIOPS

The muscles and tendons activating the hand bear a close resemblance to those found in the human hand, The following variations however, were noted in the extrinsic flexors and extensors.

## THE EXTRINSIC FLEXORS

The flexor pollicis longus is not an independent muscle as in man, but is part of the flexor digitorum profundus. (Fig. 52). The tendon is under-developed and devoid of a Synovial ~~tendon~~ sheath. Man alone has enough differentiation to have a strong flexor of the thumb, separate from the common

Fig. 54 Dorso-lateral aspect of the hand. (C. Aethiops).

Note the presence of the extensor pollicis longus, the abductor pollicis and the absence of the extensor pollicis brevis.

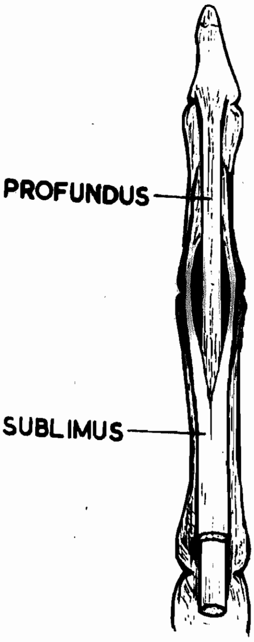

Fig. 55 The disposition of long flexor digital tendons.

Note the splitting of the flexor digitorum sublimus tendon, through which the tendon of the flexor digitorum profundus passes to insert into the distal phalanx.

profundus muscle.

## THE EXTRINSIC EXTENSORS

In man, the deep extensor group of tendons, the extensor digitorum profundus, is extremely reduced, whereas in the monkey the full compliment of deep extensors, with the exception of the extensor pollicis brevis (Fig. 54) is usually present. The extensores proprii of digits, 2, 3 and 5 are complete. (Fig. 53) whereas in man only those to the index and little fingers are generally present.

## THE DIGITAL FLEXOR MECHANISM

The digital flexor mechanism of C. Aethiops (Figs. 55 and 56) is almost the exact anatomic and functional counterpart of that in the human hand. The flexor digitorum profundus and flexor digitorum sublimis tendons are enclosed in a common synovial sheath which extends from the distal palmar crease to the terminal phalanx. The two tendons with their common synovial sheath are enveloped in a snugly fitting fibro-osseous tunnel as they cross the proximal phalanx. At the junction of the proximal interphalangeal joint the sublimis tendon splits, the profundus passing between its divergent slips.

## THE MOVEMENTS OF THE HAND OF C. AETHIOPS

By direct observations of active movements of the hand of the animal in its cage, and by cinematography and stimulation of the muscles under anaesthesia, the conclusion was reached that apart from the movements of the thumb, the hand of the monkey has a range of movement equal to, or even exceeding that of man.

Opposition of the thumb is distinctly limited. The limitation of movement in this digit is readily appreciated when the lack of independence of the flexor pollicis longus tendon and absence of the extensor pollicis brevis muscle is recalled.

## CONCLUSIONS

A comparative study of the hand of C. Aethiops, apart

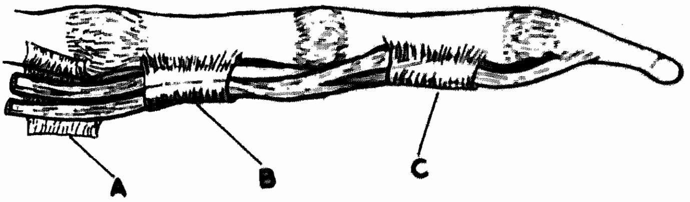

Fig. 56 The annular ligaments or pulleys. (C. Aethiops).

A. Pulley at metacarpophalangeal joint.
B. Pulley at proximal phalanx.
C. Pulley at middle phalanx.

from differences in the thumb, revealed no remarkable distinctions in anatomy or function. The opinion voiced by Wood Jones that "the difference between the hand of a man and the hand of a monkey lies not so much in the movements which the arrangements of the muscles, bones and joints makes it possible for either animal to perform, but in purposeful volitional movements which under ordinary circumstances the animal habitually exercies", has been corroborated. The view expressed by Thomas Carlyle stating that "the use of tools is man's distinguishing feature" is most appropriate and concise, a distinction which is undoubtedly attributable to the highly developed cerebral cortex in man.

## (4) THE FATE OF AUTOLOGOUS VENOUS GRAFTS IN THE VERVET MONKEY.

It had already been established that a transplanted vein would survive in the human, and before conducting a controlled experiment it was decided to determine the fate of an autologous venous graft in the monkey.

Accordingly, an experiment was performed in which venous grafts were placed around the sutured palmaris longus tendon. This procedure was adopted to assess the viability of the transplanted vein, the reaction of the tissues to its presence and the production of a tendon "sheath." At the same time this preliminary experiment enabled one to study the habits of the animal under experimental conditions, to perfect a method of anaesthesia, to test the technique of ensheathing a tendon with a vein graft and to evolve a satisfactory method for the immobilisation of the limbs of the animal following the operation. Animals are extremely intolerant to any form of splintage.

Furthermore, a method for assessing the functional results of tendon suture was evolved before proceeding to the controlled experiment. (Page 80)

### MATERIALS AND METHODS

### Care of the Animals

The animals were housed individually in metal cages measuring 5 x 4 x 3 feet. Their diet consisted mainly of sweet potatoes, tomatoes, bananas, cabbage leaves and an ample supply of carrots. On this diet they thrived. They all belonged to the male sex, and their weights varied between 8 and 12 lbs.

For purposes of identification of the animals, it was found that labelling the cages only was not sufficient, as on one occasion two of the animals were misplaced, and consequently were confused with others undergoing research of a different nature and were lost to the experiment. Each animal was therefore tatooed on the left chest with Indian ink to avoid future confusion and misfortune.

### Anaesthesia

The animal was drawn to the side of its cage by traction on a light chain which was attached to a leather strap securely tied around its waist. Once "pinned" to the wall of the cage, its back in contact with the bars, both hind limbs were cautiously withdrawn through the parallel longitudinal bars using a metal hook, and the limbs held firmly and securely. The animals were often highly resentful and vicious. Traction on the chain was then released.

The hair on the posterior aspect of the calf was shaved and light digital pressure applied to the popliteal fossa. This manoeuvre invariably revealed the presence of an easily accessible vein, corresponding in position to the lesser saphenous vein in the human. At this stage a peculiar change in the behaviour of the animal was frequently noted. The determined resistance to interference would often cease, and if food was lying within reach of the animal, it would often, apparently unconcernedly, pick it up and eat it as though nothing was amiss.

The skin of the calf was swabbed with Tinct. Merthiolate. A small syringe with a fine hypodermic needle (gauge 21) attached, was then loaded with 3 ccs. of veterinary Nembutal (Abbott. gr. I per cc.) and the solution slowly injected intravenously. The first effect, noted after the injection of I cc., was a generalised paralysis and loss of consciousness followed by slowing of respiration. Sufficient depth of anaesthesia was indicated by closure of the eye-lids and loss of the corneal reflex. The rate of respiration, normally about 18 to 20 per minute, dropped to between 10 and 15 per minute, and increased in depth. The time taken over the injection was about I minute, and the desired depth of anaesthesia was achieved in 2 to 3 minutes. Depending on the weight of the animal, the volume of anaesthetic solution injected varied from 1.25 to 2.0 ccs. With the larger doses used initially, it was found that an unnecessarily prolonged and deep anaesthesia was produced, and in two animals death resulted, probably from respiratory failure, after periods of 18 and 24 hours respectively. Subsequently it was noted that with the smaller doses used, a single injection of 1.5 ccs. would achieve adequate anaesthesia for at least 3 to 4 hours.

One of the animals which died 24 hours after the administration of the anaesthetic, was lost through a technical error. Despite the injection of 2 ccs. of Nembutal it was noted that the animal would not lose consciousness. This unusual behaviour was incorrectly presumed to be due to deterioration of the Nembutal or tolerance to the drug. Consequently, a further 1 cc. was administered and only after 4 to 5 minutes did the animal show signs of commencing anaesthesia. On removing the animal from its cage the rate of respiration rapidly fell to about 8 per minute, finally falling to about 4 per minute after 24 hours when the animal died. The cause of death was ascribed to the following error in anaesthetic technique. The diameter of the thigh of the animal was larger than the space between the bars of the cage. Consequently, on withdrawing its hind limb from the cage, obstruction to the venous return ensued. Due to the obstruction, the drug could not enter the systemic circulation to produce its desired effect. Release of the traction on the limb allowed the large pent up quantity of Nembutal (3 ccs. in all) in the congested veins to enter the circulation and this was responsible for the fatal outcome. A post-mortem was performed and revealed the presence of collapse at both lung bases, undoubtedly the result of respiratory failure consequent on an overdose of Nembutal.

## THE OPERATION

A. In each of five monkeys, the palmaris longus tendon was exposed above the wrist. The tendon was divided and sutured

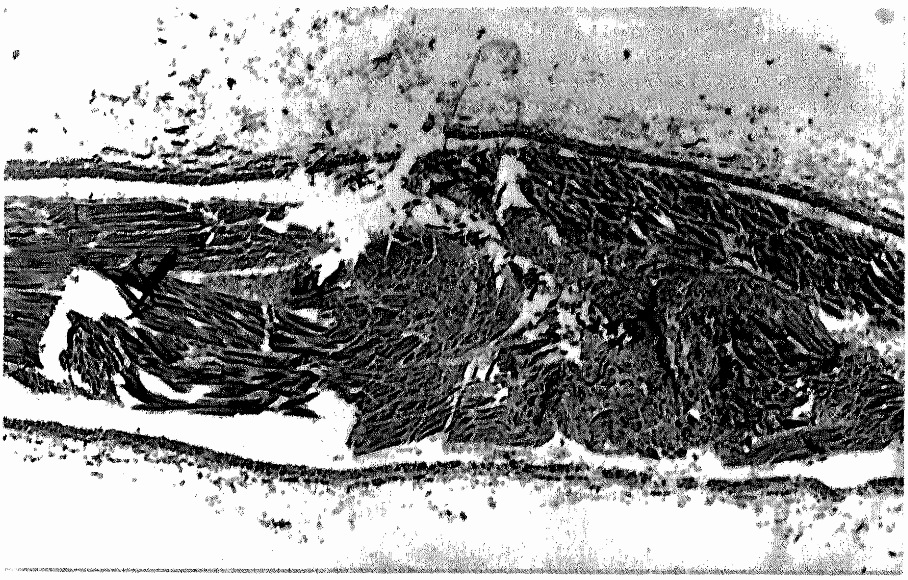

**Fig. 57** Photomicrograph of the palmaris longus tendon (monkey I) surrounded by a venous graft.
Haematoxylin and Eosin X 25

This is a longitudinal section through the suture line. The tendon has healed well, and the junction is slightly fusiform. The venous graft is not intimately adherent to the tendon. The reaction of the tendon to the suture material is minimal.

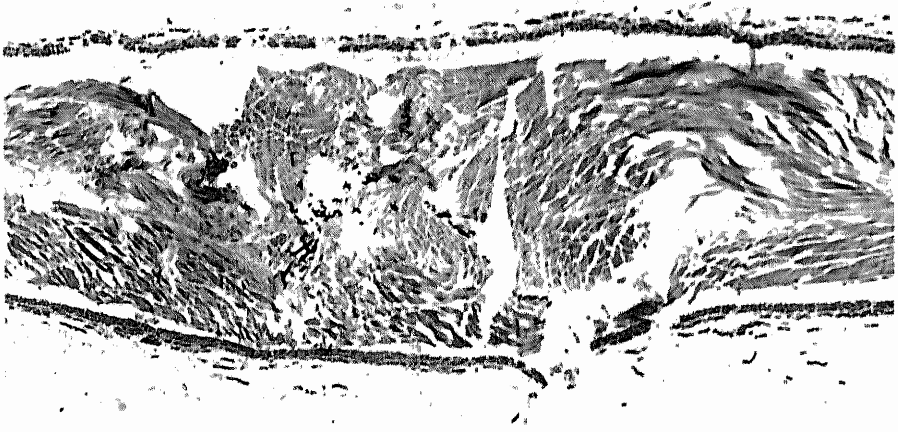

**Fig. 58** Photomicrograph of the palmaris longus tendon (monkey 2) surrounded by a venous graft.
Haematoxylin and Eosin X 25

This is a longitudinal section through the suture line. The tendon has healed well. The venous graft is not intimately adherent to the tendon. The reaction around the suture material is minimal. The tendon was immobilised for 25 days and allowed functional activity for 30 days.

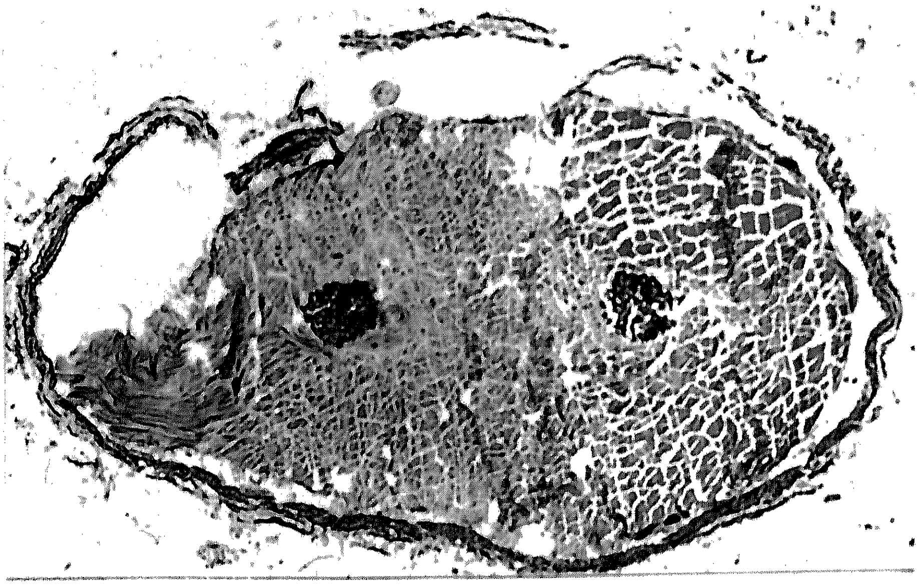

Fig. 59 Photomicrograph of the palmaris longus tendon (monkey 3) surrounded by a venous graft.
Weigert-von Gieson X 40

This is a transverse section through the tendon in the region of the suture line. There is no obvious reaction around the suture material. The venous graft is not intimately adherent to the tendon. The tendon was immobilised for 18 days and allowed functional activity for 26 days.

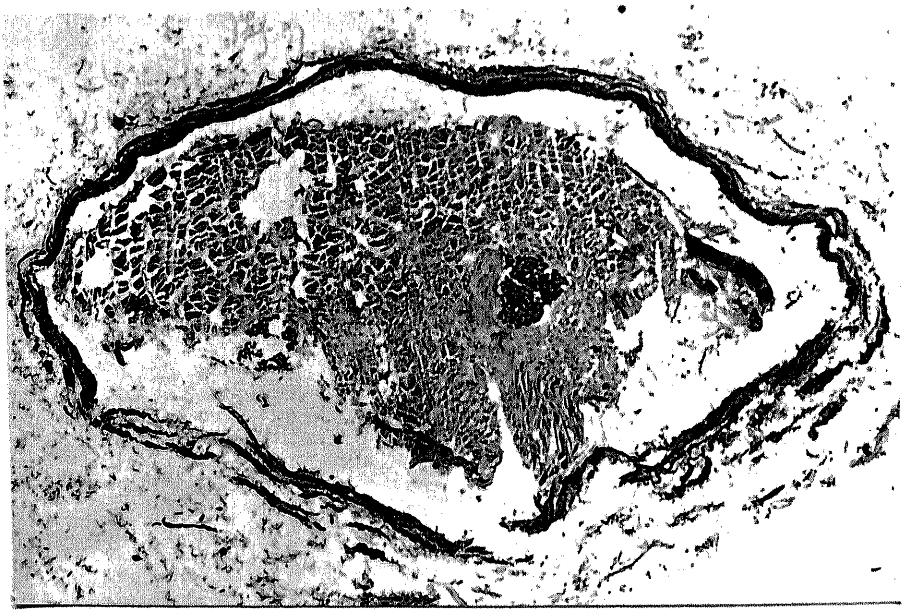

Fig. 60 Photomicrograph of the palmaris longus tendon (monkey 4) surrounded by a venous graft.
Weigert X 40

This is a transverse section through the tendon and venous graft in the region of the suture line. The venous graft is not intimately adherent to the tendon. The reaction around the suture material is minimal. The tendon was immobilised for 22 days and allowed functional activity for 33 days.

Fig. 61 Photomicrograph of the palmaris longus tendon (monkey 5) surrounded by a venous graft.
Weigert-von Gieson X 40

In this specimen the palmaris longus and adjacent tendons were removed en bloc. This section was cut at approximately 1 cm. from the suture line. Note the venous graft containing elastic fibres surrounding the tendon. The vein in this section is not intimately attached to the tendon, but at the suture line it was adherent.

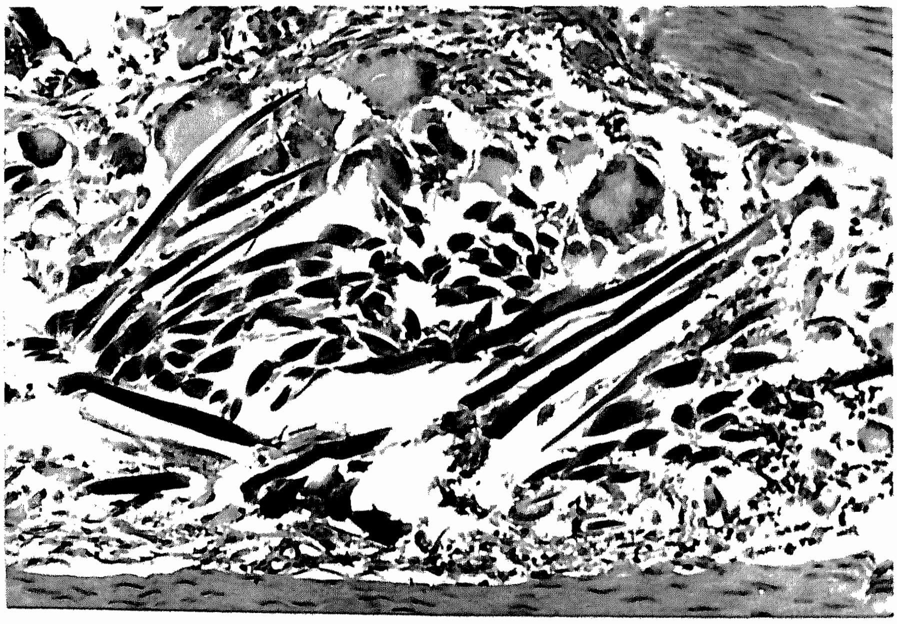

Fig. 62 Photomicrograph of a longitudinal section of palmaris longus tendon to show the suture material and the surrounding tissue reaction. (monkey 5).
Haematoxylin and Eosin X 300

Note the jet black strands of suture material which have been sectioned longitudinally transversely and obliquely. Numerous foreign body giant cells, and small round cells are present.

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with silk*, and a venous graft excised from the external jugular vein used to ensheath the site of suture. The technique used was the same as that employed in the controlled experiment and is described in full on page 89. The wrist joints were immobilised in flexion using plaster casts, for periods varying between 18 and 25 days.

Following periods of active use varying between 15 and 40 days, the tendons with their surrounding venous grafts were exposed, excised, examined macroscopically and then sectioned.

## THE RESULTS

The skin incisions had healed well, leaving thin linear scars. Macroscopically, the tendons were well united, the suture lines anastomoses being slightly fusiform but showing no obvious evidence of separation of the sutured ends. Examination after excision revealed that the tendons could be made to glide within their venous grafts. Although adhesions were evident between the tendons and venous grafts, they were flimsy and translucent and could be dissected with ease.

Microscopically, although endothelial lined tendon sheaths were not demonstrated, the adhesions that formed did not intimately unite the venous grafts to the tendons (Figs. 57, 58, 59, 60 and 61). The reaction of the ~~tissues~~ ~~to the~~ tendons and tissues surrounding ~~presence~~ surrounding of the venous grafts was not remarkable. Most of the muscle fibres in the tunica media had degenerated, but the evidence of elastic fibres in the tunica adventitia ~~was evident~~ ~~in~~ all the sections. had shown little change

The reaction of the ~~tissues~~ tendons to the suture material was extremely variable despite the fact that the identical suture material was used throughout. In some instances the reaction was chronic as characterised by the presence of giant cells, lymphocytes, plasma cells and reticulum cells (Fig. 62). Occasionally, the reaction was frankly acute; numerous

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*No. 00 Black Braided Silk. (John Weiss & Son. Ltd.)

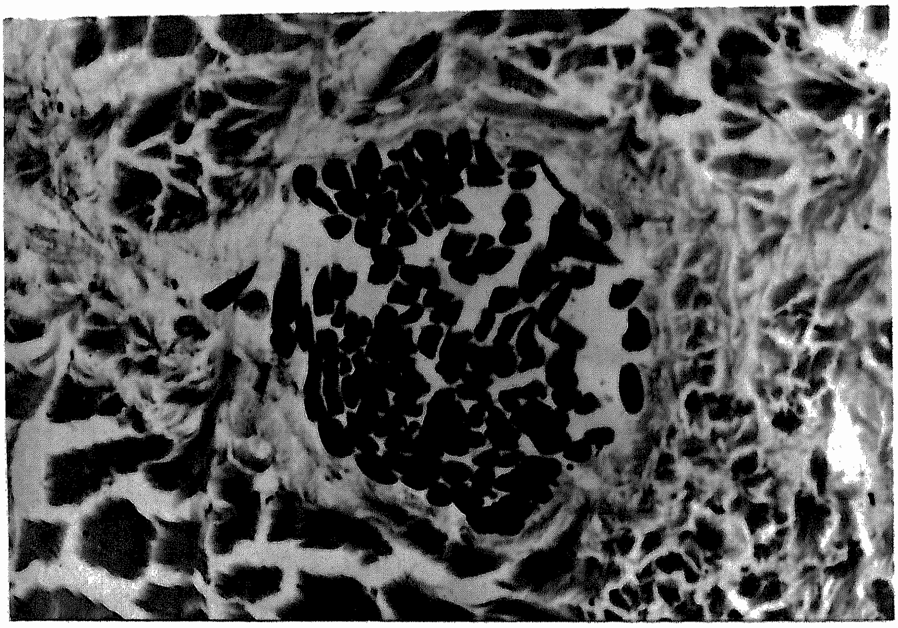


Fig. 63 Photomicrograph of the suture material in a tendon, showing no obvious reaction. (monkey 4).

Haematoxylin and Eosin X 300

The tendon has been sectioned transversely. Note the suture material, with no obvious surrounding tissue reaction. The tendon was immobilised for 18 days and allowed functional activity for 26 days.

polymorpho-nuclear leucocytes and red cells surrounded the suture material. Occasionally no reaction was evident. (Fig. 63).

In view of the fact that the reaction around some of the sutures was minimal or absent, and maximal around others, it is possible that the suture material per se was not responsible, but rather sepsis, introduced at the time of the operation.

## CONCLUSIONS

The venous grafts surrounding the palmaris longus tendon had survived for periods up to 59 days, without obvious evidence of tissue irritation. Although no tendon sheaths were produced, the adhesions that formed between the venous grafts and tendons were flimsy and mobile and excellent passive gliding was possible between the two structures.

C

## (5) THE CONTROLLED EXPERIMENT

The evaluation of the results of tendon repair by a statistical analysis can be very misleading in that too many variables are encountered. The location of the injury, the time interval between the accident and the repair, the degree of contamination at the time of injury, the number of tendons involved, the magnitude of damage to soft tissues, nerves and joints, the cicatricial index of the individual, the nutrition of the finger, the technique employed, and the experience of the surgeon are all significant factors which influence the result.

From the point of view of scientific accuracy, it was imperative to develop a well controlled experiment in which variables could be dispensed with as far as possible, and to devise adequate standards and methods for determining function and to express the results with as much precision as possible. Unfortunately, many of the investigators engaged in experimental tendon surgery failed to appreciate the true significance of the word "function" and used the term synonymously with tendon gliding. A digital flexor tendon and its sheath may be anatomically intact, but if the activating muscle is unable to contract, or the peritendinous connective tissues scarred, or the interphalangeal joints ankylosed, the tendon is functionally useless. Furthermore, in the assessment of the result of a flexor tendon repair, not only should the range of flexion be the sole consideration, but also the ability of the finger to flex against resistance. The latter is an index of the capacity of the digit to do work.

### A resume of the Method of Control and Assessment of Function

Throughout the controlled experiment, a routine was adopted which was strictly followed.

The normal range of flexion of the distal interphalangeal joints of the index and middle fingers of the experimental animal was determined by electrical stimulation of the flexor digitorum profundus of those digits, and the movements recorded photographically. The range of flexion obtained at the distal interphalangeal joint was regarded as an index of the degree of gliding of the flexor digitorum profundus tendon. In an attempt to assess the work performed, a weight was attached to the phalanx and the degree of flexion against the resistance was recorded. The information derived from this latter procedure, however, was difficult to evaluate, and was not used in the final assessment of the results.

The digital sheaths of these fingers were then incised, the flexor digitorum profundus tendons exposed and divided. In the index finger, a venous autograft ~~an autologous venous graft~~ about three quarters of an inch in length excised from the external jugular vein, was threaded over one of the free ends of the tendon, and the tendon ends sutured. The venous graft was then brought over the site of suture to act as an artificial tendon sheath. The digital sheath of the middle finger was similarly exposed, but the divided and sutured tendon was not "ensheathed" by a venous graft. The middle finger therefore acted as the control. After varying periods of time, the range of flexion of the digits operated upon was re-determined, and thereafter the fingers amputated and sectioned to determine the reaction of the tissues to the presence of a venous graft. Certain features were particularly sought for, namely, the presence or otherwise of a synovial-like sheath, the state of the vein as regards its survival, the presence and extent of peritendinous adhesions, and finally the state of tendon union and the reaction caused by the suture material.

In the author's opinion, the method of investigation employed in this experiment, satisfied important desiderata in that:-

1. The experiment was confined to tendons in the digital sheath, an area notoriously liable to adhesion formation and one which offered the most rigid test of operative technique.

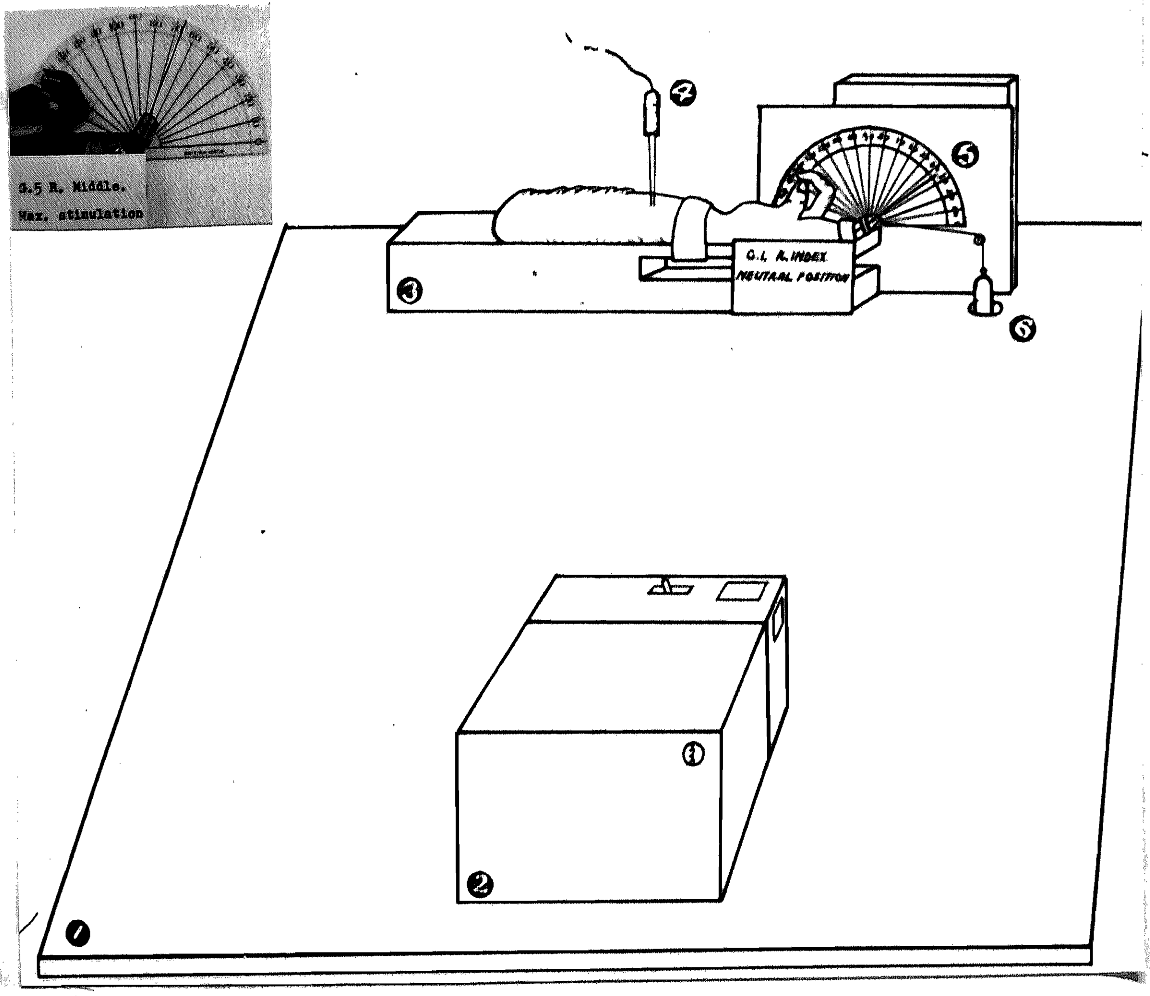


Fig. 64 Diagram of the apparatus employed to record the range of flexion at the distal interphalangeal joint.

(1) - The base of the apparatus.
(2) - The camera used for recording the range of flexion. Two 500 watt photo-flood lamps, one on each side of the camera, were used to illuminate the object.
(3) - The platform on which the forearm and hand of the anaesthised animal was placed and immobilised with strips of adhesive cellophane tape. The distal phalanx of the digit under test was not immobilised and thus had freedom of motion. The indicator which recorded the position of the distal interphalangeal joint was attached to the distal phalanx by means of an encircling strip of adhesive tape.
(4) - The stimulating electrodes over the motor point.
(5) - The protractor which recorded the range of flexion, supported by the wooden upright.
(6) - The lead weight which was attached to the nail of the digit by means of a fine thread. To prevent fouling of the weight by the platform, the weight was transferred by passing the thread over the pulleys as illustrated.

Inset A minature photographic specimen of a digit under test.

2. The digital flexor mechanism of the experimental animal presented features structurally and functionally comparable to that in man.
3. The method was well controlled in that apart from the use of the venous graft in one finger, the technique employed throughout was identical.
4. Adequate standards for determining function were instituted.
5. The presence or absence of an artificial tendon sheath was determined by the study of histological sections.

## MATERIALS AND METHODS

### The Apparatus used to record the Range of Flexion at the distal interphalangeal joint

Fig. 64 is a schematic diagram of the apparatus employed to record the range of flexion at the distal interphalangeal joint. Although simple in design and inexpensive, it was devised and constructed only after considerable trial and error.

The apparatus consists of a wooden base measuring 15 x 20 inches, on the far side of which is attached a platform on which the forearm and hand of the anaesthetised animal rests. The right half of the platform is slotted throughout its entire breadth to enable strips of adhesive cellophane tape to encircle the wrist and hand for immobilisation of the limb. That portion of the platform on which the finger to be tested rests, is grooved longitudinally to accommodate the digit.

Throughout the experiments, the right index finger, followed by the right middle finger was placed on the platform in the supine position, and maintained there by means of strips of adhesive cellophane tape. The terminal phalanx of the finger however was left unsupported as illustrated. Generally, three strips of adhesive tape sufficed for fixation of the hand and wrist to the platform. One strip of adhesive tape was placed across the proximal two phalanges, a second across

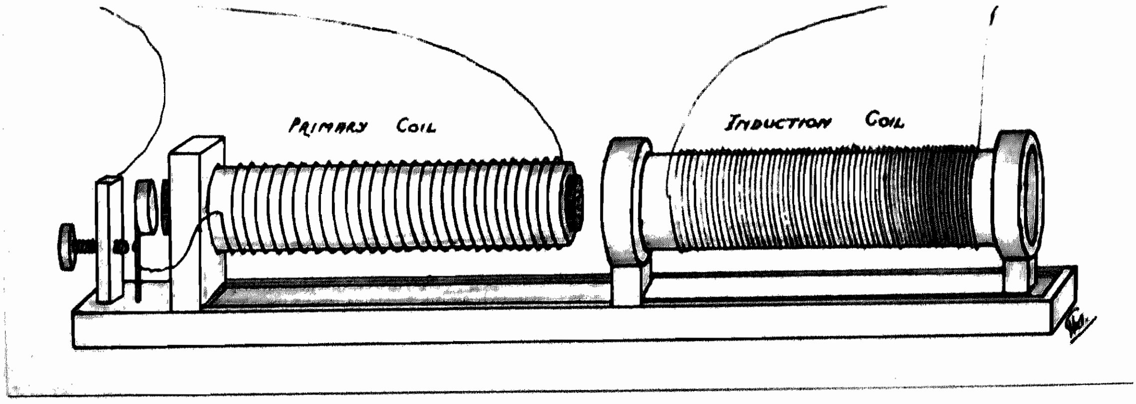


Fig. 65 The Induction Coil.

The primary coil is connected to a dry cell of 1.5 volts. To produce faradisation, a trembler interrupter, Neef's hammer, is included in the primary circuit. The stimulating electrodes are connected to the secondary or induction coil which is mounted on the movable sledge. The centimetre scale which was affixed to the base of the apparatus has been deliberately omitted to avoid overburdening of the diagram with too much detail.

the palm, and a third across the wrist joint. The whole hand was thus immobilised with the exception of the terminal phalanx, which was allowed unrestricted movement on stimulation.

## Measurement of Flexion at the distal interphalangeal joint

A celluloid protractor with a measuring range of 180° was placed adjacent to the digit, and supported there by a vertical wooden upright behind the platform. A sheet of white cardboard which acted as a photographic background for the digit, was interposed between the protractor and the wooden upright. By means of an adjustable mechanism, the position of the protractor could be varied so that the zero marking of the protractor coincided with the long axis of the proximal two phalanges, and the 90° graduated mark intersected the distal interphalangeal joint.

An indicator, consisting of the shaft of a fine hypodermic needle one and a half inches long, was fixed to the lateral aspect of the terminal phalanx nearest the camera and was secured there by a piece of adhesive tape a quarter of an inch wide, wound around the phalanx. The indicator was adjusted to coincide with the long axis of the terminal phalanx. A white rectangular sheet of paper was attached to the front of the platform, below the finger to be tested. Recorded on the paper, were the identification number of the animal, the name of the digit, and the nature of the procedure being performed.

## Stimulation of the Digital Flexor Mechanism

An electrical stimulus in the form of a faradic current derived from an induction coil, was used to stimulate the flexor digitorum profundus muscle and thus produce flexion of the distal interphalangeal joint.

## The Induction Coil used

Fig. 65 is a schematic diagram of the induction coil used. It is similar in construction to the Lewis Jones coil designed at the beginning of the present century for the purpose of obtaining painless contraction of muscles. The primary coil and interrupter are in circuit with a dry cell of 1.5 volts. The current used for stimulation is derived from the secondary or induction coil which is mounted on a movable sledge. The intensity of the current is regulated by moving the sledge so as to slide the secondary coil over the primary. The more completely the two coils overlap the stronger the current and vice versa. A centimetre scale affixed to the base of the apparatus indicates the distance between the two coils and thus indirectly the intensity of the current. The stimulating electrodes which are connected to the secondary coil consist of two straight suture needles, inserted through a rubber teat, the points of the electrodes being situated about one sixteenth of an inch apart.

### The Effects of Faradism and the Reason for its use

A faradic current is an intermittent, asymmetrical, alternating current produced from the winding of the induction coil, and the physiological effect of faradic stimulation of muscles differs very little from that obtained by other forms of electrical stimulation. Its method of accomplishing the muscular contraction, however, differs from that of other electrical currents. The effective phase of the secondary faradic current occurs at the "break" period, and the frequency of these "break" phases varies directly with the vibrations of the hammer. In the induction coil used, the number of "break" phases varied between 50 and 90 per second, as revealed by the stroboscope. At this rate, the "break" stimuli follow one another so rapidly that muscle, with an intact nerve supply, has no time in which to relax between stimuli, and a smooth even tetanus results. A tetanic contraction was most desirable for these experiments in order to allow time for the photographic recording of the ranges of movement.

The sensation produced by faradic stimulation depends chiefly on the duration of each individual "break" current flow. If this is short, there is little or no sensation of pain, but if it is long, there may be considerable production of pain. (Harris 1947). This fact was well borne out in preliminary experiments when it was noted that when using a faradic current in a lightly anaesthetised animal, slow vibrations produced contractions of muscles not directly stimulated, indicating a protective withdrawal reflex, the result of painful stimuli. To minimise painful stimuli the vibration hammer was adjusted to its maximal frequency, about 90 vibrations per second.

## Theoretical objections to the use of the Induction Coil

Physicists consider the induction coil a poor instrument for quantitative work. The frequency of vibration of the hammer and the resistance of the platinum contacts are variable, factors which produce rectification and a wave form full of irregular harmonics. These phenomena would appear to be of significance in the assessment of the results in these experiments, because according to Harris "slow vibrations produce bigger and more painful contractions than quick ones!"

A test was then made to determine whether variations in the frequency of the vibrating hammer did occur, and what effect this phenomenon would have on the degree of muscular contraction. With the adjustable screw of the vibrating hammer locked, the stroboscope revealed slight variations in the frequency of vibrations, but no significant changes were observed in the degree of muscular contractions, provided the stimulus was maximal.

## Motor Points - The areas of muscle stimulation

Charts of motor points in the human, in textbooks on physical medicine locate the excitor areas for the flexor digitorum profundus muscle of the index and middle fingers on the volar aspect of the middle third of the forearm. In the monkey the "points d'election" do not correspond to those of

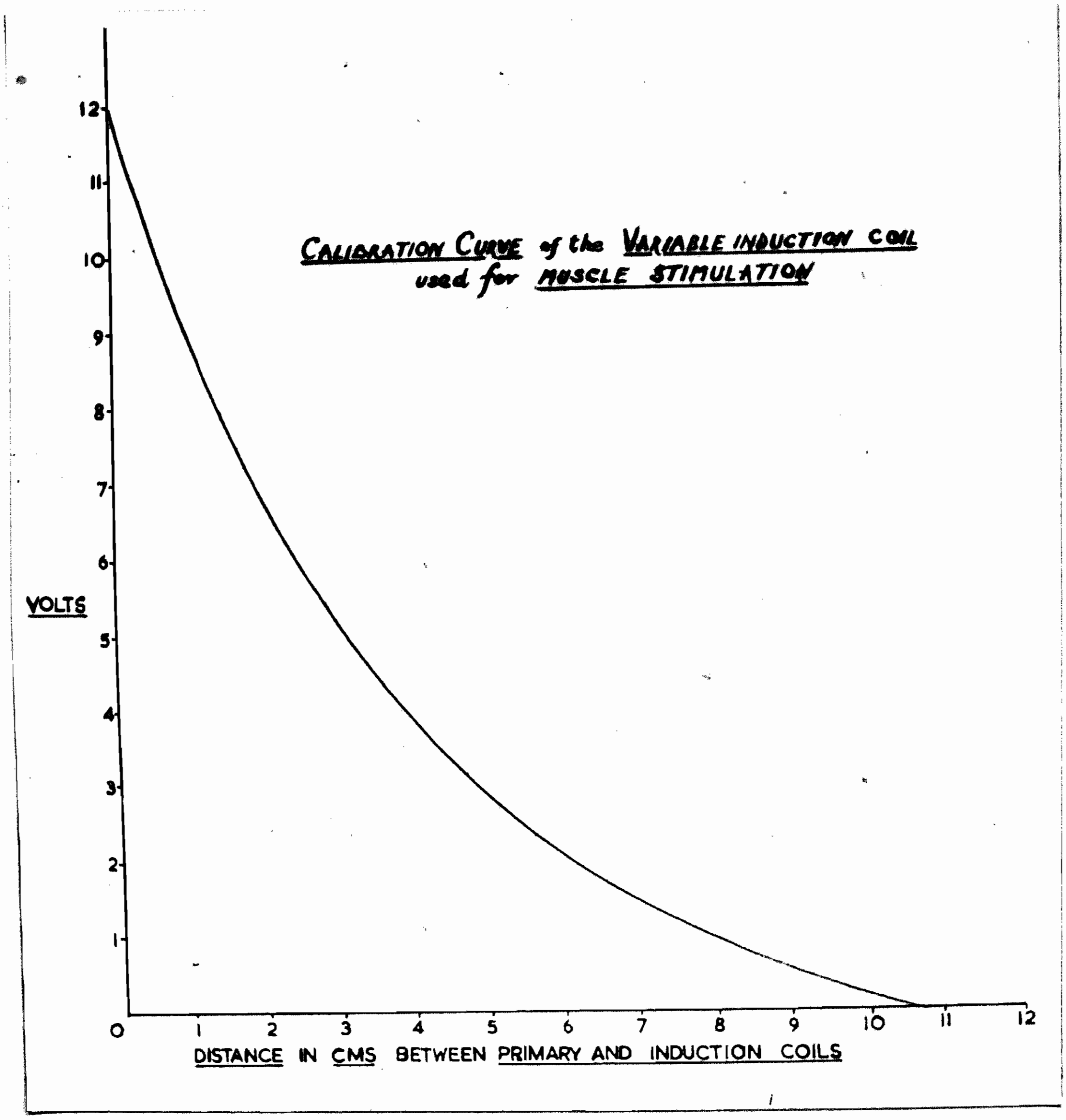


Fig. 66 The Calibration curve of the Induction Coil.

Note that the voltage output of the induction or secondary coil is inversely proportional to the distance between the primary and secondary coils.

the human. Examination of at least 12 monkeys, revealed that the motor points of these muscles were constantly situated within an area roughly the size of a threepenny bit on the antero-lateral aspect of the forearm about two inches proximal to the wrist joint. Motor points are stated to correspond to the point of entrance into a muscle of the motor nerve, but dissection of the flexor digitorum profundus muscle in the monkey to confirm this statement, revealed that the median nerve actually entered the muscle proximal to the motor point. This finding gives one the impression that the motor point does not necessarily correspond to the entry of the nerve into the muscle.

## Calibration of the Induction Coil

To obtain maximal flexion of the distal interphalangeal joint a maximal stimulus had to be delivered to the activating muscle. It was therefore essential (a) to calibrate the induction coil in volts and (b) to determine the strength of stimulus necessary for a maximal contraction. Table 7 illustrates the voltage output of the secondary coil relative to the distance between the primary and secondary coils.

| SECONDARY COIL OUTPUT (VOLTS) | DISTANCE BETWEEN PRIMARY AND SECONDARY COILS (CM) |
|---|---|
| 0.25 | 10.0 |
| 0.5 | 9.3 |
| 1.0 | 8.0 |
| 1.5 | 7.4 |
| 2.0 | 7.0 |
| 2.5 | 6.7 |
| 3.0 | 6.3 |
| 3.5 | 6.0 |
| 4.0 | 5.6 |
| 4.5 | 5.3 |
| 5.0 | 5.0 |

Table 7. The voltage output of the secondary coil and the distance between the primary and secondary coils.

Fig. 66 is a graph showing the calibration curve produced by plotting the values from Table 7 against each other. Note

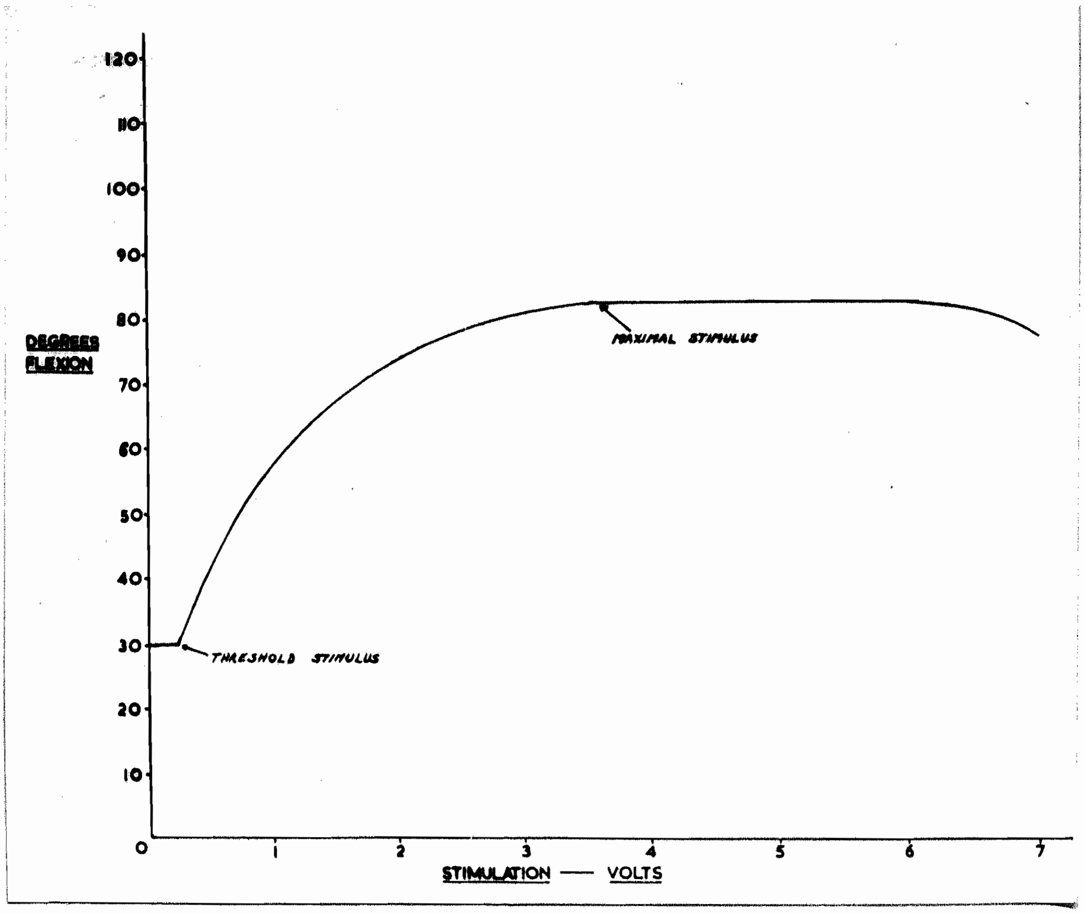


Fig. 67 Graph showing the effect of stimuli of increasing intensity on the degree of flexion of the terminal interphalangeal joint of an index finger.

Note 1. The position of rest of the terminal interphalangeal joint was 30° flexion.

2. Stimuli of increasing intensity produced active flexion only when the threshold stimulus was reached, i.e. 0.25 volts. Stimuli of intensity of less than 0.25 volts were therefore subminimal.

3. An increase in voltage resulted in increased flexion, and maximal flexion occurred when the intensity of the voltage was 3.5. Stimuli of intensity greater than 3.5 volts did not produce further flexion. Therefore 3.5 volts was the maximal stimulus. The slight reduction in the degree of flexion noted at the end of the graph, was due to muscular fatigue, the result of repeated maximal stimuli.

that the output of the induction coil is inversely proportional to the distance between the primary and secondary coils.

## Stimulation of the Digital Flexor Muscles

Stimuli of increasing intensity were then delivered to the flexor digitorum profundus muscle to determine the stimulus necessary for maximal flexion of the distal interphalangeal joint. Fig. 67 is a graph showing the effect on the muscle of changing the strength of the stimulus. The position of rest of the terminal interphalangeal joint of the index finger was 30° flexion. On stimulating the motor point no active flexion occurred until the intensity of the stimulus reached 0.25 volts, that is, the threshold stimulus. Thus stimuli of intensity less than 0.25 volts were therefore subminimal. On increasing the voltage, the maximal degree of flexion occurred when the intensity of the stimulus was 3.5 volts, that is, the maximal stimulus. Further increase in the voltage produced no further increase in flexion. This is in accord with the well known physiological law which states that an increase in the intensity of a stimulus above the maximal stimulus will not produce increased contractions. After repeated maximal stimuli at short intervals, the maximal stimulus failed to produce a maximal contraction owing to the onset of muscular fatigue. This point is noted in the graph.

Throughout the experiments a stimulus of at least 4 volts was delivered to the flexor digitorum profundus muscle and the degree of flexion recorded. The voltage was then increased to confirm that the stimulus was maximal.

## The Photographic Recording of Flexion at the distal interphalangeal joint

The camera used was a simple box camera (Film size $3\frac{1}{4}$" x $4\frac{1}{2}$"). In order to obtain a close view of the object, a +2 dioptre eye-sight testing lens was attached to the front of the aperture, and this procedure reduced the focal length and gave a depth of focus of about one-third of an inch, which

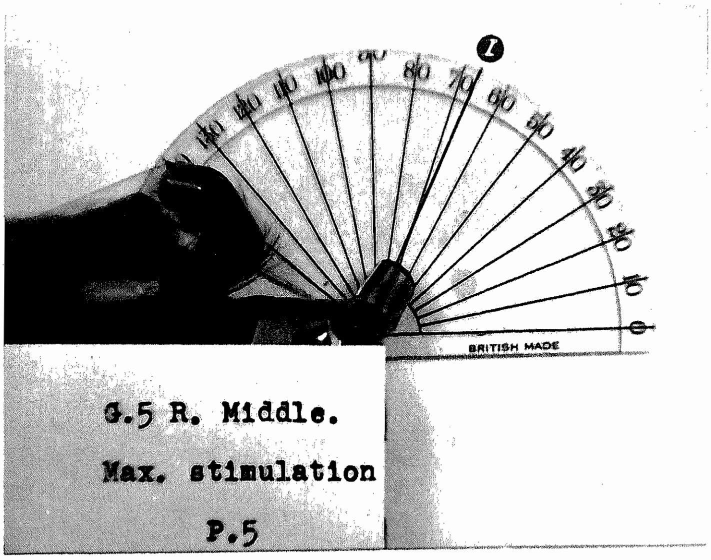


Fig. 68 Errors in the photographic recording of the degree of flexion.

This photograph, picked at random, records the degree of flexion of the terminal interphalangeal joint to be 67° as revealed by the position of the indicator (I). On careful examination, it is noted that the long axis of the proximal two phalanges does not coincide with the zero marking on the protractor, and furthermore the indicator attached to the terminal phalanx, does not coincide with the long axis of that phalanx. The photographic reading is therefore incorrect. Refer to Fig. 69 for the method of correction.

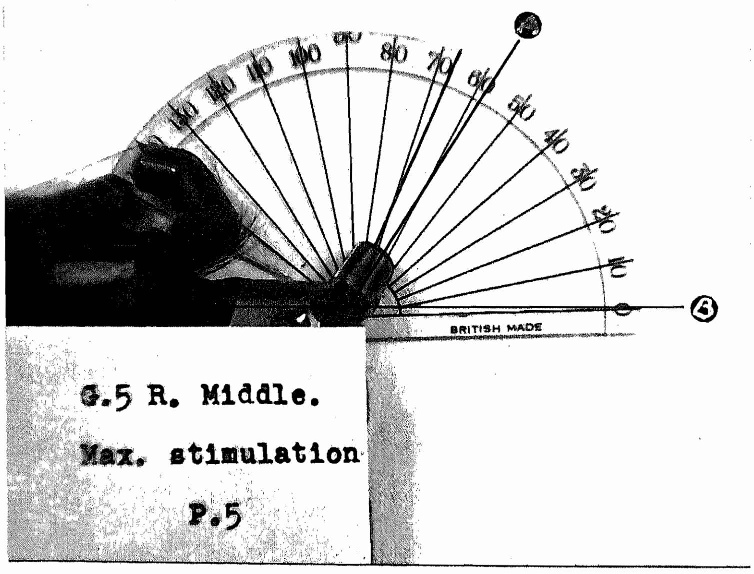


Fig. 69 The method of correction of errors in the photographic reading.

Two straight lines, represented by (A) and (B) have been projected to coincide with the long axis of the terminal phalanx and proximal two phalanges respectively. The malalignment of the protractor and indicator relative to the long axis of the proximal two phalanges and terminal phalanx is now obvious. The angle formed by the two straight lines is the correct angle and when measured with a protractor, is found to be 57°. Thus 57° is the true reading.

was adequate for clear definition. The films were of a high Weston rating - either Kodak Super XX or Gevaert 32°. The illumination was derived from two 500 watt photo-flood lamps set about sixteen inches apart and fourteen inches from the object. The time of exposure was one-twentyfifth of a second, with the aperture wide open (f16).

The hair on the volar aspect of the distal forearm was shaved and the skin moistened with normal saline. A photograph was taken of the neutral position of the terminal interphalangeal joint. The motor point for stimulation of the flexor digitorum profundus of the index finger was located by varying the position of the electrodes on the surface of the skin using a minimal stimulus. Having located the relevant motor point, a maximal stimulus was delivered and the maximal degree of flexion recorded photographically.

### The degree of Flexion against Resistance

To determine the degree of flexion against resistance, a 50 gm. lead weight was attached to the nail of the phalanx by means of a length of thin thread. To prevent fouling of the weight by the side of the platform, which would have occurred had it been allowed to hang vertically from the nail, the weight was transferred by passing the thread over a pulley as illustrated in Fig. 63. The flexor digitorum profundus muscle was then stimulated, using a maximal stimulus and the degree of flexion against resistance was recorded.

The same procedures were then carried out on the middle digit - the control.

### Errors in the Photographic Readings and their Correction

Examination of Fig. 68, a photograph chosen at random, reveals the photographic position of the distal phalanx to be 67° flexion. Close scrutiny of the photograph, however, shows that the long axis of the proximal two phalanges does not coincide with the zero marking of the protractor. Furthermore, the indicator, showing the position of the terminal phalanx does not accurately coincide with the long axis of this phalanx. Therefore the photographic reading is misleading incorrect and suitable adjustments had to be made. This was done as follows. Two lines were projected, one (a) coinciding with the long axis of the distal phalanx and the other (b) coinciding with that of the proximal two phalanges. The angle so formed was measured and was regarded as the true or <u>corrected</u> reading. (Fig. 69).

Accurate positioning of the protractor so that its zero mark coincided with the long axis of the proximal two phalanges was difficult, on account of the fact that the design of the recording apparatus made it difficult for the eye to view the axis of rotation of the terminal interphalangeal joint end on. Consequently errors of parallax resulted. The malalignment of the indicator relative to the long axis of the distal phalanx is due to the fact that during flexion, the movement of the skin in proximity to the interphalangeal joint caused slight displacement of the indicator. To prevent the slight movement of the indicator during flexion of the phalanx it was originally decided to insert the indicator into the phalanx itself. This procedure was fraught with complications - the possibility of osteomyelitis or a pulp space infection, and the intention abandoned.

## THE OPERATION

In few fields of surgery do minor disturbances of wound healing interfere so seriously with the end results as in tendon surgery. Time, patience, and care were employed throughout to conform to an atraumatic, haemostatic technique. The instruments used were simple and of light construction. Only haemostats of the mosquito or Halstead variety were used, and tissue forceps of the type used by the ophthalmic surgeon. Scissors of the manicure type enabled the ligatures to be cut close to the knots. Exposed tissues were kept constantly moist with normal saline.

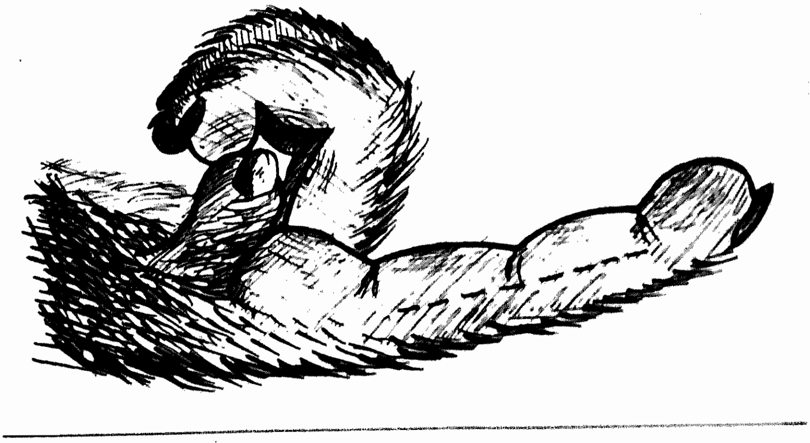


Fig. 70 The skin incision

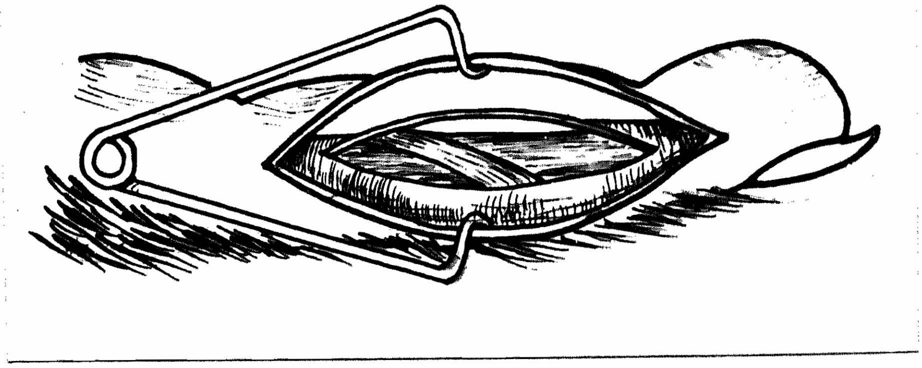


Fig. 71 The skin and tendon sheath have been divided exposing the flexor digitorum profundus and sublimus tendons. Note the self retaining skin retractor, constructed from a safety pin.

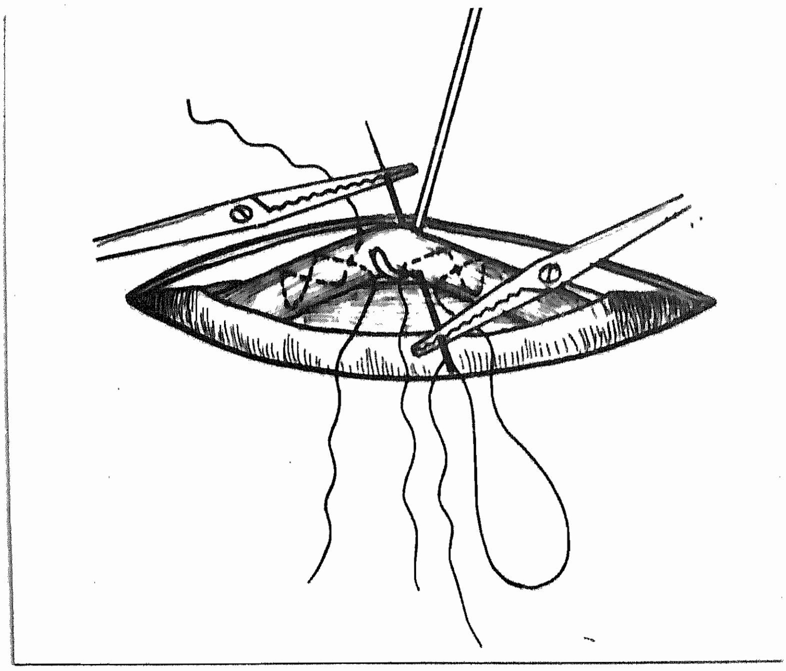


Fig. 72 The method of inserting the tendon sutures.

The blunt curved hook elevates and steadies the tendon while the sutures are inserted. The advantages of this method are obvious. Following division of the tendon, there is no necessity to excise the traumatised stumps and axial rotation of the stumps is eliminated when the sutures are tied.

## The Skin Preparation

The hair on the right hand, wrist and forearm and the left side of the neck was shaved, the skin thoroughly washed with warm water and soap, and the surface swabbed with Tinct. Merthiolate. Towelling cloths, with small slits in their centres, to expose only the sites of operation, were then placed in position.

## The Exposure of the Digital Flexor Tendons

To steady the relatively small digit while operating, a stay suture was inserted through the nail and attached to a haemostat which was allowed to hang over the side of the operating table and thus exert traction.

Through an incision one inch in length along the lateral surface of the digit (Fig. 70) the tendon sheath was exposed and incised longitudinally in the line of the skin wound. (Fig. 71). A small self retaining retractor, constructed from a safety pin, was used to effect skin retraction. A tourniquet was not necessary to produce a bloodless field; haemorrhage was not a problem and was easily controlled by gentle swabbing. On two occasions the volar digital artery was cut, and was arrested by crushing, using the points of a fine haemostat, without having to resort to the use of ligatures. The digital sheath having been incised, the two slips of the flexor digitorum sublimus tendon were lifted out of the sheath by means of a blunt hook, and the terminal inch of this tendon excised up to its insertion into the base of the middle phalanx.

## Division of the Flexor Digitorum Profundus Tendon and the Method of Suture

(A) Prior to the division of the flexor digitorum profundus tendon, the sutures of 00000 braided nylon were inserted into the intact tendon as illustrated in Fig. 72. The reasons for this procedure were as follows:

The usual technique for steadying a tendon prior to the insertion of the suture, is to grasp the divided end with a pair of artery forceps. This inevitably results in crushing of the tendon ends and necessitates the excision of the traumatised portions, which would amount to the loss of approximately a quarter of an inch of the tendon length. In the monkey, the loss of a quarter of an inch of tendon length is considerable extensive, and consequently, after tying the sutures, the tendon tension would be increased -(thus predisposing to a factor conducive to disruption at the suture line) pulling out of the sutures, despite immobilisation of the wrist and fingers in full flexion.) Should the sutures hold however, the tendon would be of shorter length and following healing might prevent full extension.

(B) The suture material used was a No. 00 black braided ligature silk. (John Weiss and Son Ltd.) This diameter suture material appears to be relatively thick but the description of the sizes of the numerous types of silk is not uniform. Some brands are designated by letters and others by numbers, and seldom are two identical. To convey an idea of the thinness of the thread used, the diameter as measured by the micrometer was .004 inches which corresponds roughly to a No. 000000 "Deknatel" Nylon. The needles used for suture were straight, three quarters of an inch long, .01 inches in diameter and non-cutting. Such a small needle was not procurable on the market and was specially prepared by grinding and polishing the thinnest available needle.

(C) Using a blunt hook to steady the tendon, the suture material was introduced into the tendon in the form of a lacing suture, using a minimum of suture material. There are advantages and disadvantages to the many methods of suture but this method was preferred because it is simple, provides firm anchorage in the tendon, produces little disruption of its fibres, and does not burden the tissues with a great amount of suture material. This type of suture, in addition, leaves the opposed tendon ends free of suture material following tying

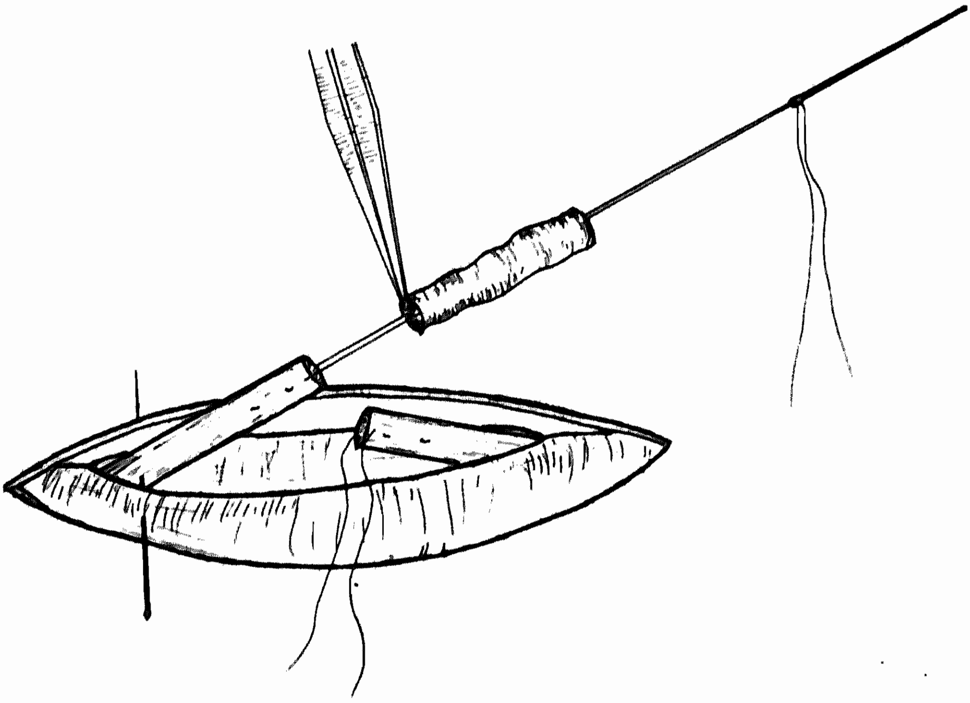


Fig. 73 The method of threading the venous graft over the tendon.

The suture in the proximal tendon stump is threaded through a blunt straight needle. The venous graft is then threaded over the needle and suture and staggered over the proximal tendon stump (Fig. 74). Note the needle passing through the proximal part of the digital sheath and flexor digitorum profundus tendon. This step facilitates the tying of the sutures without having to exert tension.

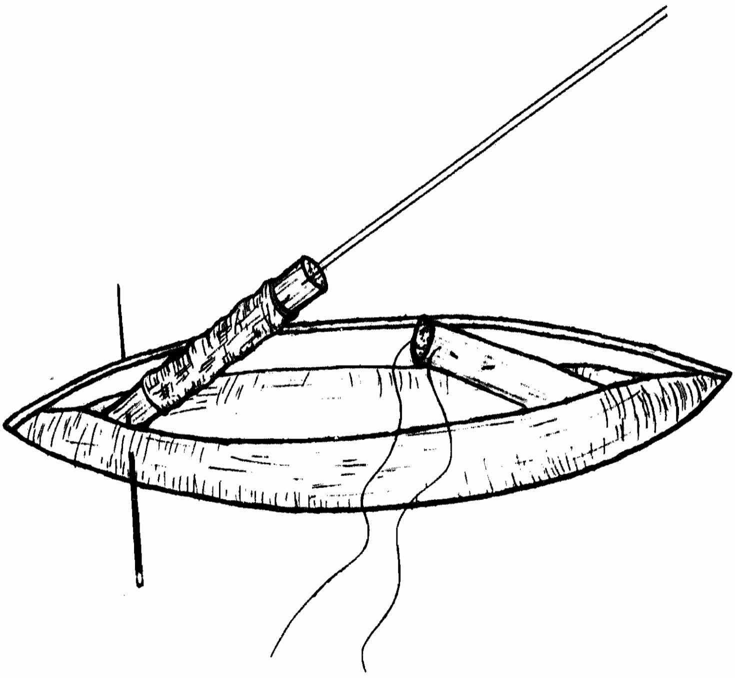


Fig. 74 The venous graft staggered over the proximal tendon stump.

of the knots.

Commencing near the proposed line of tendon division and using two needles for each suture, two sutures were inserted so as to allow a gap of about one eighth of an inch between them. (Fig. 72). A moist saline swab was then placed over the wound, and the operation directed to obtaining the venous graft from the neck.

## The Excision of the Venous Graft

The left side of the neck having been previously shaved, cleaned, and towelled, a transverse incision one and a half inches long was made through the skin an inch above the clavicle. The platysma muscle, better developed than in man, was not divided, but split in the direction of its fibres. The external jugular vein was readily located by blunt dissection and isolated from its bed. A notable feature was the invariable spasm of the vessel which accompanied its dissection. Two fine silk ligatures were placed around the vein one inch apart and the distal ligature always tied first. This step caused distension of the vein and usually resulted in the disappearance of the spasm. The proximal ligature was then tied and the segment of vein between the two ligatures excised. The external diameter of the vein varied between one eighth and one sixteenth of an inch. Holding the vein open with fine non-toothed dissecting forceps, the lumen was irrigated with normal saline, using a fine calibre pipette, to wash out any residual blood. The vein was then immersed in normal saline and the skin incision in the neck sutured with No. 000 plain catgut interrupted sutures.

## "Sheathing" the Tendon with the Venous Graft

Having isolated the vein graft, the operation was redirected to the exposed tendon.

As an auxiliary step, a fine straight needle was inserted through the proximal part of the tendon and sheath to prevent retraction of the tendon after division. (Fig. 73). This

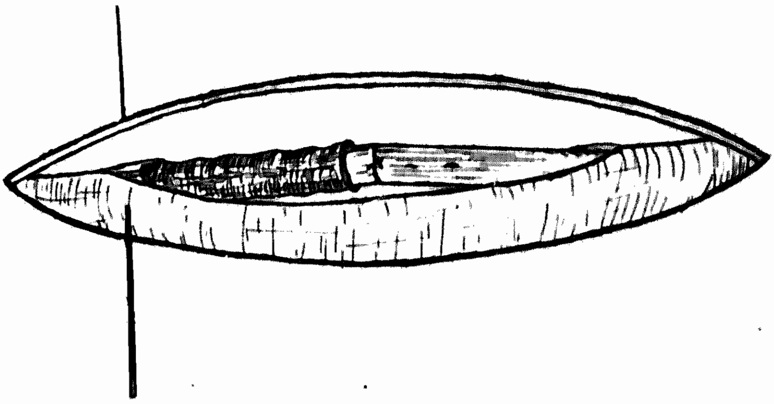


Fig. 75 The tendon sutures have been tied without having to exert tension on the sutures.

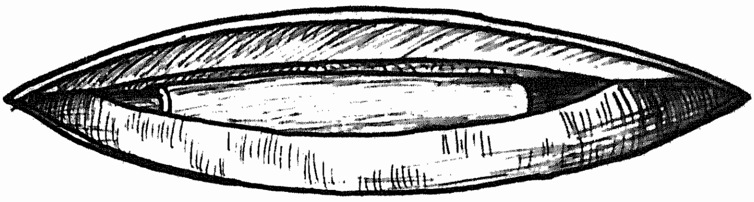


Fig. 76 The venous graft has been brought over the site of the tendon suture.

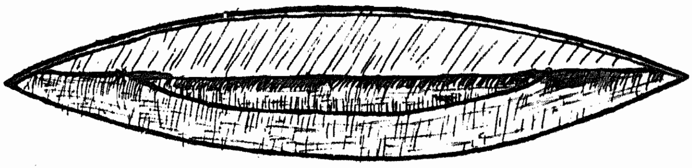


Fig. 77 The venous graft has been anchored to the proximal and distal ends of the incision in the tendon sheath. The tendon sheath has not been sutured.

facilitated the tying of the sutures without tension. Using a sharp scalpel, the tendon was divided between the two sutures. Both free ends of the proximal suture were then threaded through a straight blunt needle, and holding the lumen of the vein open with fine forceps, the needle and the suture were threaded through the vein, which was staggered over the free end of the tendon. (Figs. 73 and 74). In one instance difficulty was encountered in "sheathing" the tendon with the venous graft. After numerous attempts, the vein had to be discarded, owing to the trauma inflicted on it, and a fresh specimen of vein had to be used. The reason for this difficulty was soon apparent when the vein was cut longitudinally and its intimal surface examined - it contained two valves, unlike the external jugular vein of the human which is valveless. This discrepancy in comparative anatomy was soon elucidated. The monkey does not always assume the erect posture and consequently the venous return from the head and neck must be assisted in overcoming the effect of gravity to prevent cerebral congestion in the position of inversion. Both sutures were then tied and the vein drawn across the suture line (Figs. 75 and 76). The ends of the vein were then anchored with single silk sutures to the proximal and distal ends of the incision in the tendon sheath. (Fig. 77). The diameter of the lumen of the vein was adequate to ensure absence of tension on the wall of the vein. Having ensured complete haemostasis, the skin was sutured with No. 000 plain catgut interrupted sutures. No attempt was made to suture the digital sheath or reconstruct the pulleys. Originally it was intended to excise that portion of the digital theca in relation to the newly constructed sheath. This procedure would have caused unnecessary trauma and would have violated one of the fundamental principles in tendon surgery, namely, the atraumatic technique. The idea was soon abandoned.

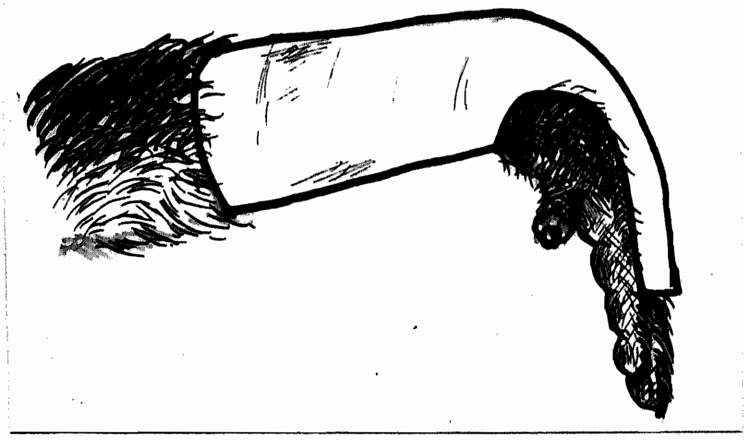


Fig. 78 The wrist immobilised in flexion. The plaster cast extended to the terminal phalanges and not to the proximal interphalangeal joints as depicted in the illustration.

A The tendon sheath of the middle finger was then exposed and the same operation performed on the flexor digitorum profundus tendon without ensheathing the sutured tendon with a venous graft. B. The tendon of this finger acted as the Control. The skin wounds were then swabbed with Tinct. Merthiolate and C a dry dressing applied. ✗ The wrist joint was immobilised in about 80° flexion by means of a dorsal plaster slab extending from the upper forearm to the terminal phalanges. (Fig. 78). The period of immobilisation was varied from [illegible] With the wrist in flexion the flexor muscles were deprived of D strength but could still undergo a little exercise of movement. ✗

The recording of the pre-operative range of movements and the operative procedure took from two and a half to three and a half hours to complete owing to the repeated adjustments that had to be made to the recording apparatus, and the care required to operate on relatively minute and delicate anatomical structures. The animal was then returned to its cage protected by a blanket.

Recovery from anaesthesia took several hours and was often heralded by shivering, a response probably due to the loss of bodily warmth occurring during the operation.

## THE POST-OPERATIVE COURSE

### Removal of the Plaster from the Immobilised Hand

E It was noted that the animals became intolerant to the plaster casts and soon made attempts to remove them. This they generally succeeded in doing after periods varying from 14 to 21 days, and this obviated the necessity to administer further anaesthesia for their removal. In one of the animals, not included in the control series, the plaster cast was still intact after six weeks. The animal did not succeed in removing it himself probably owing to a thick application of plaster. Consequently, it was removed under anaesthesia.

### Observations of Active Finger Movements

Observations of the animals in their cages on frequent occasions revealed little voluntary flexion in the fingers operated upon. The handling of food by the affected hand showed the finger to be held in the almost fully extended position, with little attempt at flexion. It was therefore presumed at this stage that the fingers were "frozen" by adhesions or disuse, or a combination of both. Neither could retraction of the tendon ends be excluded. The animals tolerated captivity well, as shown by their general appearance and apparent maintenance of weight.

### The Post-operative Recording of Flexion in the Fingers

The animals were re-anaesthetised after periods varying from 85 to 267 days, and recordings of the post-operative range of movements made. The metacarpophalangeal and interphalangeal joints had a good range of passive movement. On stimulation of the flexor muscles of the fingers under observation, without strapping the limb to the recording apparatus, flexion occurred at the metacarpophalangeal joints only, with little or no flexion at the interphalangeal joints. However, on stimulating the muscles with the hand on the recording platform, (the proximal and middle phalanges being immobilised by adhesive tape), flexion at the distal interphalangeal joints did occur. One was puzzled, and temporarily at a loss to explain why movement occurred only when the proximal two phalanges were immobilised. The reason was soon obvious when it was recalled that the pulleys of the tendon were not reconstituted after the operation and therefore the digital flexor mechanism was at a great mechanical disadvantage. Flexion on the recording apparatus however, was obtained as a result of the substitution of pulleys by the retaining action of the adhesive tape.

The skin incisions had healed excellently, leaving with the exception of one animal (G.2 middle finger), no visible evidence of a scar. A further striking feature was the slight but obvious atrophy of the pulp and papillary ridges of the operated fingers with slight depigmentation of the terminal phalanges. In some instances the skin was shiny, pink and somewhat atrophic. These trophic changes were probably the result of disuse of the fingers. Having completed the recordings of the post-operative ranges of movement the index and middle digits were amputated through their respective metacarpophalangeal joints. Owing to the minuteness of the tendon and its related structures it was soon apparent that the presence of a sheath could not be determined with precision by macroscopic dissection. It was therefore imperative to prepare histological sections of the fingers en bloc.

## The Preparation of the Histological Sections and Associated Problems

In view of the specialised nature of the histological sections required in this study, certain technical difficulties were encountered, and these are described in the text that follows. In the preparation of the sections, the routine described below was adhered to throughout.

### 1. Fixation

Skin is a relatively impermeable structure and is poorly penetrated by fixatives. Mere immersion of the amputated digits in formalin solution would have prolonged diffusion and probably delayed fixation of the more deeply placed tissues. A delay in fixation was undesirable in that post-mortem structural changes might have occurred. To circumvent this possibility, a few minims of 40% formalin in normal saline were injected subcutaneously through a very fine hypodermic needle at several points around the circumference of the finger. Following this initial injection, the digits were immersed in 4% formalin in normal saline for periods varying between 4 and 6 days.

### 2. Decalcification

Originally Custer's formic acid decalcifying solution was used. Despite the immersion of the specimens in this solution for periods as long as 10 days, complete decalcification did not occur. Subsequently, nitric acid 5% was used, and proved more satisfactory. The specimens were kept in this solution for 5 to 7 days after which they were removed and washed in running tap water for 24 hours.

3. Dehydration

Following decalcification, the fingers were then processed by immersion in the following solutions in the order stated.

1. Alcohol 95% - 18 hours
2. Absolute Alcohol 18 hours
3. Benzol - 6 hours

4. Embedding and sectioning

Prior to embedding in the wax blocks, the nails were removed. This hard tissue can be softened only with Na OH, a chemical which results in disintegration of the soft tissues.

Once the digits were embedded in wax, the blocks were adjusted so that longitudinal sections of the entire digit could be cut. On reaching the centre of the digit, the remaining half of the digit was removed from the block and disarticulated at the proximal and distal interphalangeal joints. The proximal, middle and distal hemi-phalanges were then re-imbedded and sectioned transversely.

5. The Staining Reagents

The following staining reagents were employed:

1. Standard Haematoxylin and Eosin
2. Masson
3. Mallory
4. Weigert
5. Weigert-von Gieson

Indisputable identification of the venous sheath could only be determined by the demonstration of the characteristic elastic laminae. Support for this statement was evident on examining the Haematoxylin and Eosin sections in which all the connective tissues were stained uniformly pink, the identification of the vein being uncertain or impossible. Initially only Haematoxylin and Eosin stains were employed and one assumed erroneously that the vein had become completely replaced by fibrous tissue. This false impression was soon corrected when specific connective tissues were demonstrated with the special stains. Unfortunately, the Masson and Mallory stained histological sections were not of good quality owing to the previous impregnation of the specimens with acid which was necessary for decalcification.

## Difficulties encountered in Cutting the Sections

Once embedded in the opaque wax, it was not easy to see through the opaque medium and thus accurately adjust the block so that the long axis of the finger was parallel to the knife of the microtome. Consequently some of the longitudinal sections were cut somewhat obliquely. As a result the cross-sectional shape of some of the transverse sections were more than hemi-circular and others less than a hemi-circle. The longitudinal sections were cut at 7 microns and the transverse at 5 microns. Thinner longitudinal sections were not feasible on account of the density of the tissues, especially the tendon, and the length of the block which in every case was at least one and a quarter inches long.

Sections of even thickness were difficult to obtain on account of the varying densities of the component tissues. This difficulty applied especially to the tendon, which was extremely hard and even more difficult to cut than bone. The splaying or disruption of tendon fibres noted in some of the photomicrographs is therefore accounted for.

## (6) THE RESULTS OF THE CONTROLLED EXPERIMENT

Please note that throughout this section, for convenience of reference, the illustrations have been arranged to precede the text.

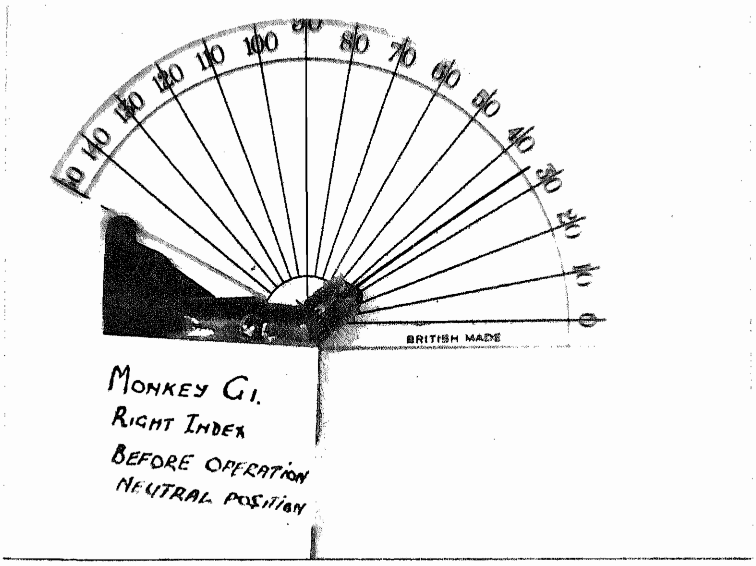


Fig. 79. Photograph of the right index finger of monkey G.I. in the Neutral Position before the operation

Photographic reading - 35°
Corrected reading - 40°

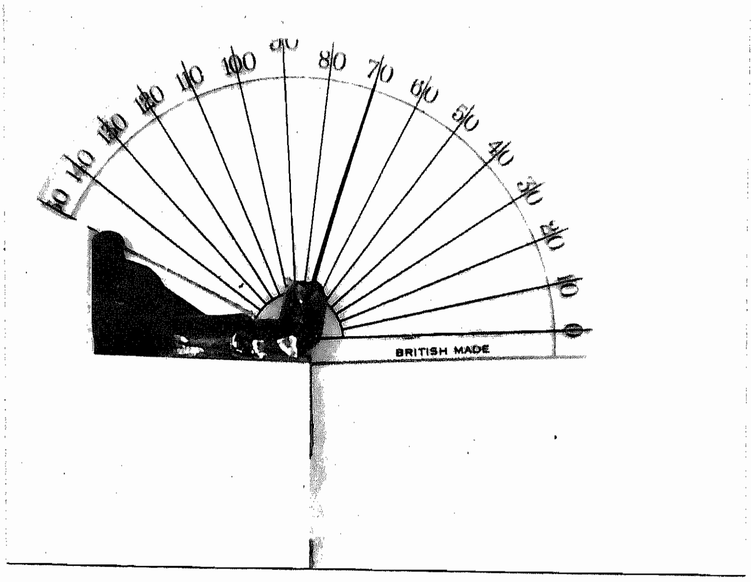


Fig. 80. Photograph of the right index finger of monkey G.I. in Maximal Flexion before the operation

Photographic reading - 70°
Corrected reading - 75°

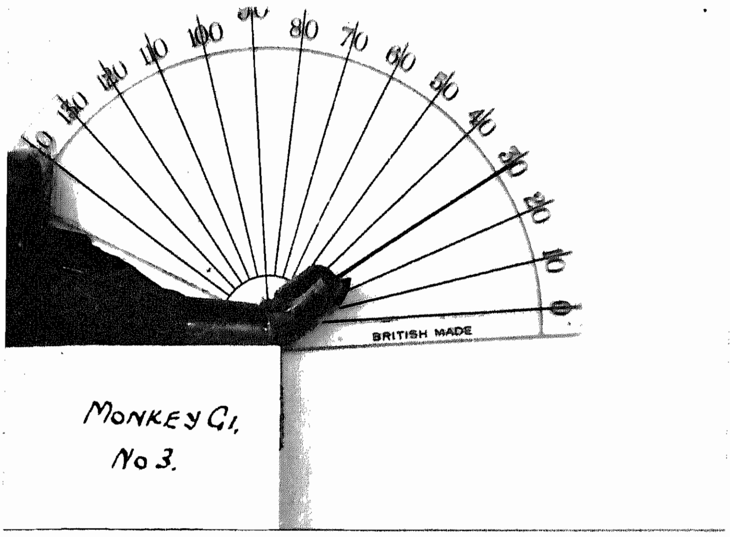


Fig. 81. Photograph of the right middle finger of monkey G.I. in the Neutral Position before the operation.

Photographic reading - 30°
Corrected reading - 38°

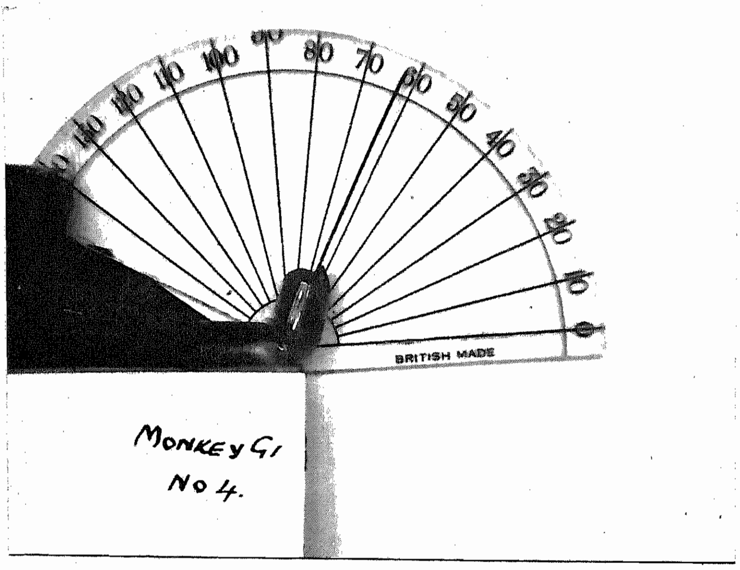


Fig. 82. Photograph of the right middle finger of monkey G.I. in Maximal Flexion before the operation

Photographic reading - 63°
Corrected reading - 75°

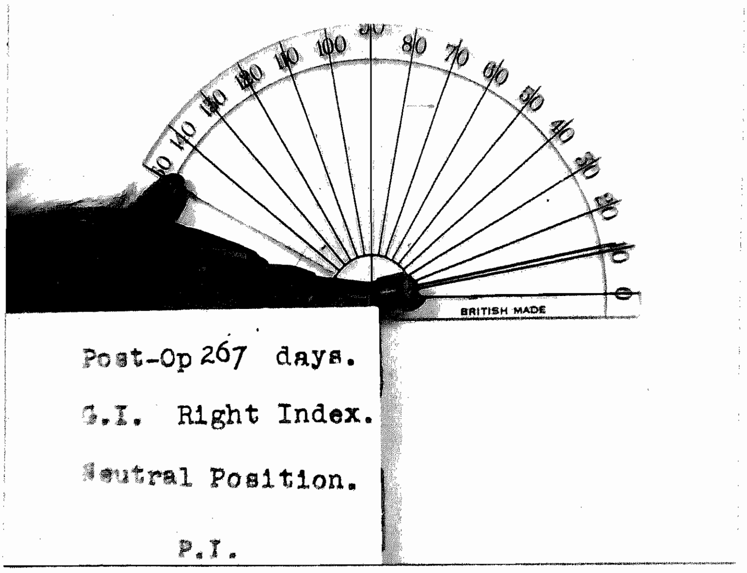


**Fig. 83.** Photograph of the right index finger (venous graft) of monkey G.I. in the Neutral Position, 267 days post-operatively.
Photographic reading - 11°
Corrected reading - 10°

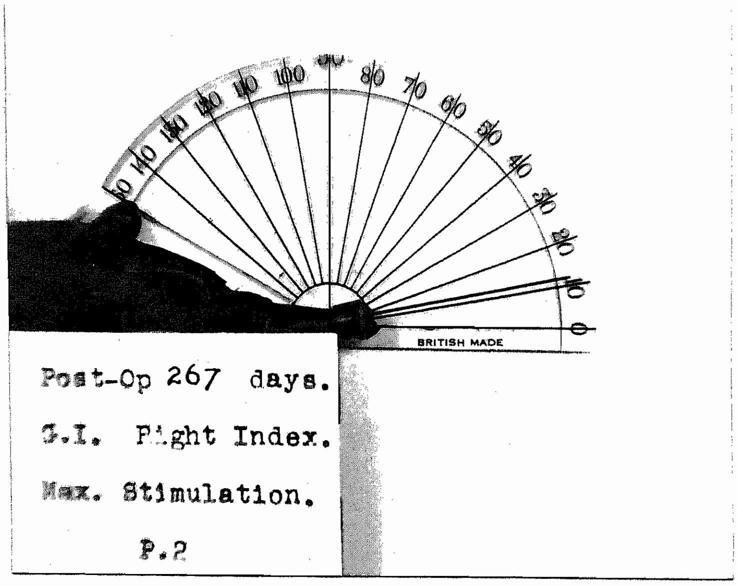


**Fig. 84.** Photograph of the right index finger (venous graft) of monkey G.I. in Maximal Flexion, 267 days post-operatively.
Photographic reading - 12°
Corrected reading - 11°

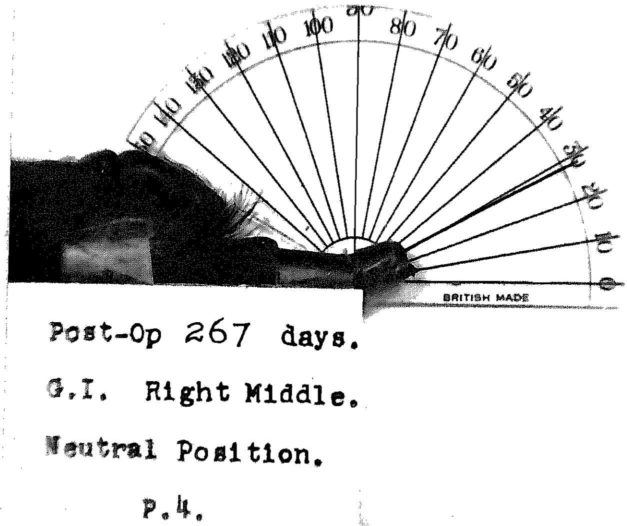


Fig. 85. Photograph of the right middle finger (Control) of monkey G.I. in the Neutral Position, 267 days post-operatively.
Photographic reading - 29°
Corrected reading - 29°

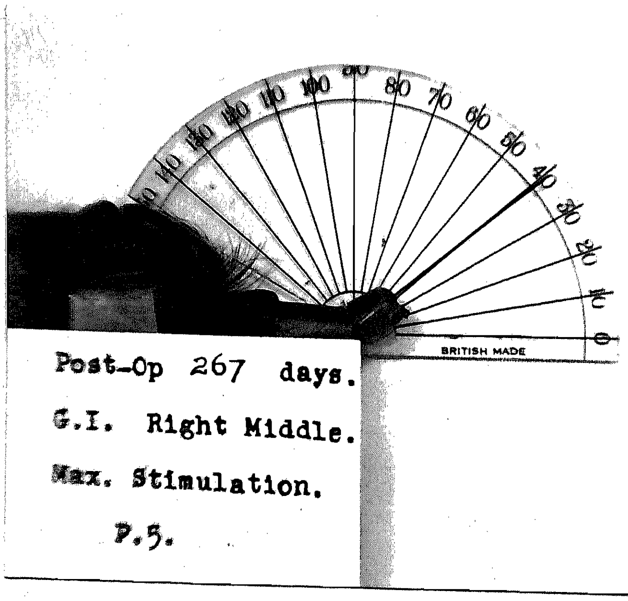


Fig. 86. Photograph of the right middle finger (Control) of monkey G.I. in Maximal Flexion, 267 days post-operatively.
Photographic reading - 40°
Corrected reading - 40°

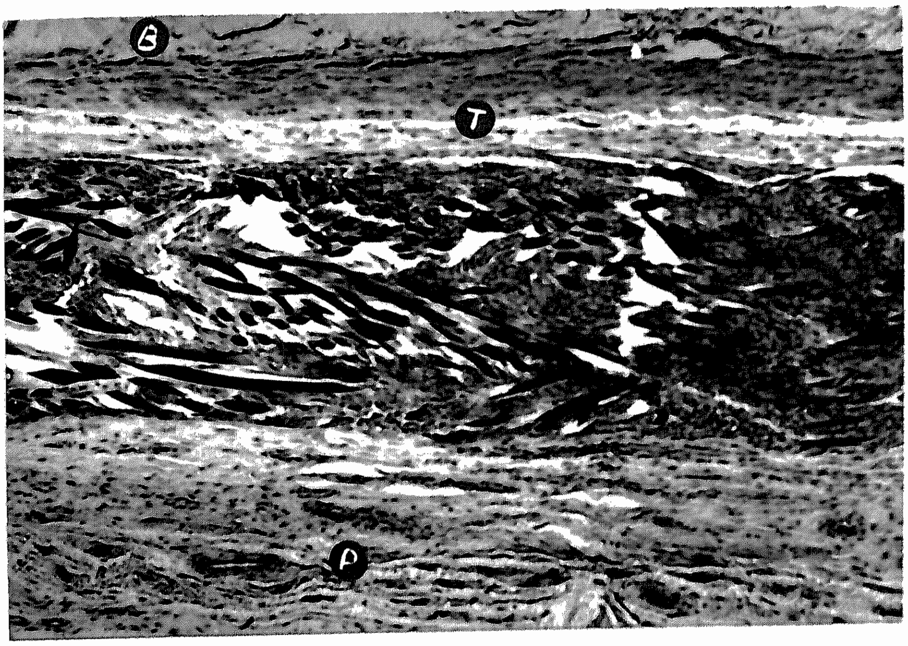


Fig. 87 Photomicrograph of a longitudinal section of the flexor digitorum profundus tendon of the index finger of monkey G.I. (Venous graft)
Haematoxylin and Eosin X 130

No tendon sheath is visible. The tendon (T) is adherent to bone (B) and peritendinous tissues (P). Note the vascularity of the peritendinous tissues and the well marked chronic inflammatory reaction surrounding the suture material.

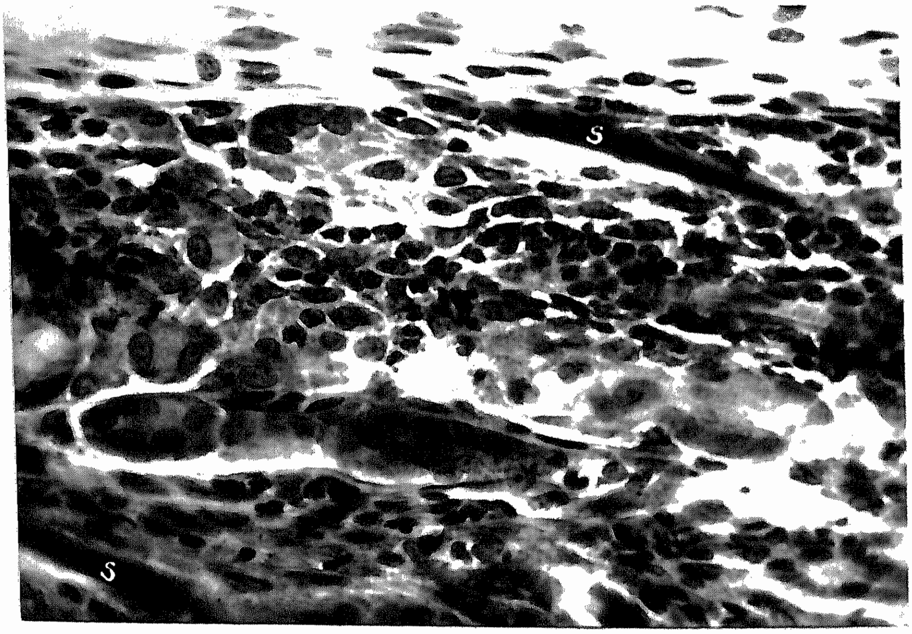


Fig. 88 High power photomicrograph of the tissue reaction surrounding the suture material.
Haematoxylin and Eosin X 425

Note the numerous small round cells and giant cells surrounding the suture material (S).

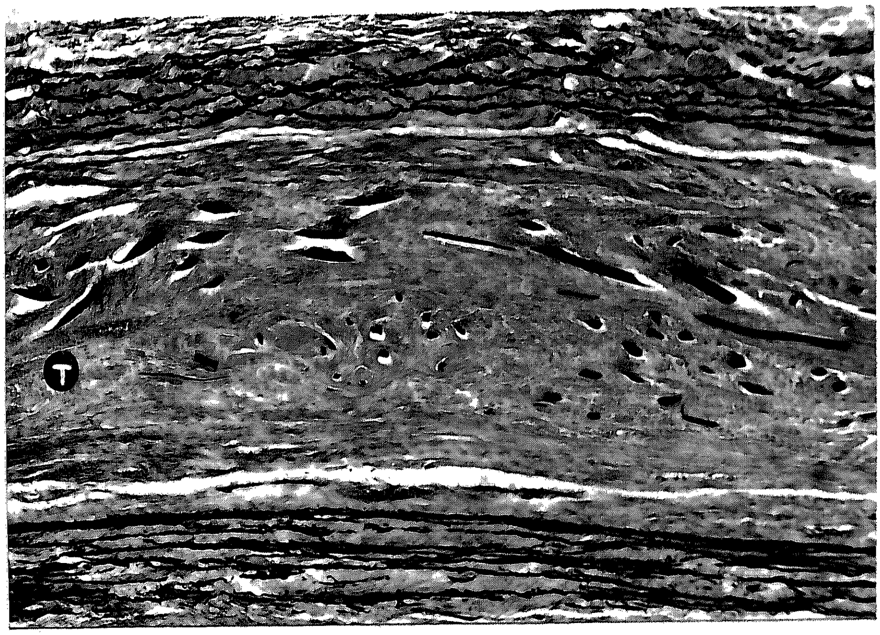


Fig. 89 Photomicrograph of a longitudinal section of the flexor digitorum profundus tendon of the index finger of Monkey G.I. to show the venous graft.
Weigert X 80

Note the venous graft containing elastic laminae surrounding the tendon (T). A suggestion of a sheath space is evident in this section but elsewhere the vein was intimately adherent to the tendon, and the architecture of the elastic laminae not so well preserved. Compare with Fig. 90.

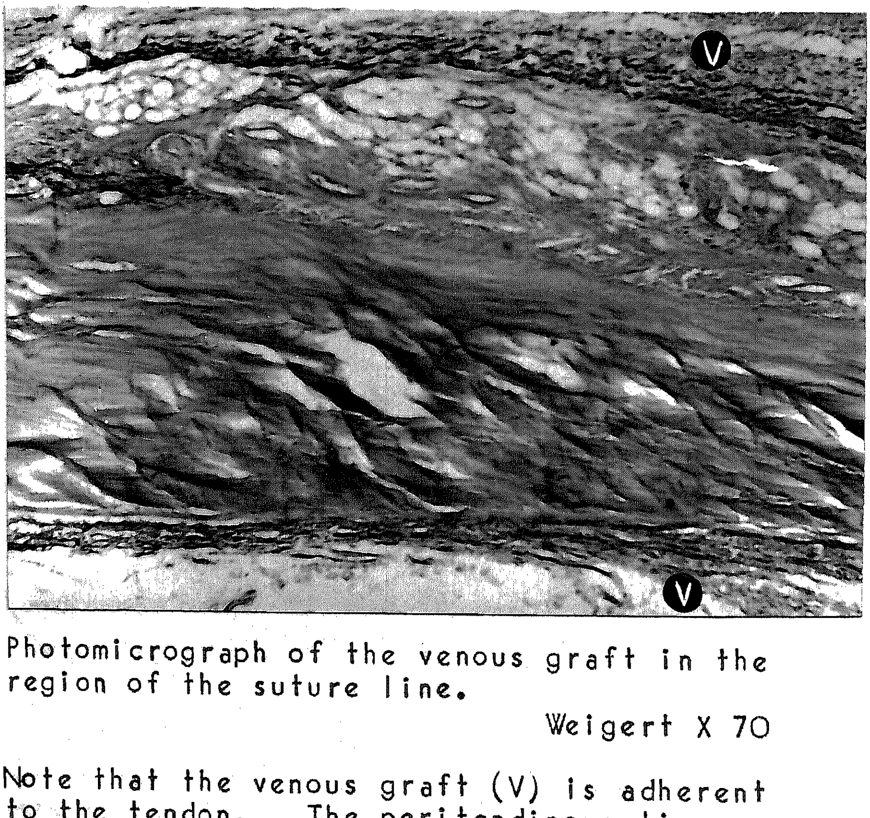


Fig. 90 Photomicrograph of the venous graft in the region of the suture line.
Weigert X 70

Note that the venous graft (V) is adherent to the tendon. The peritendinous tissues are hypertrophied, vascular, and contain numerous fat cells.

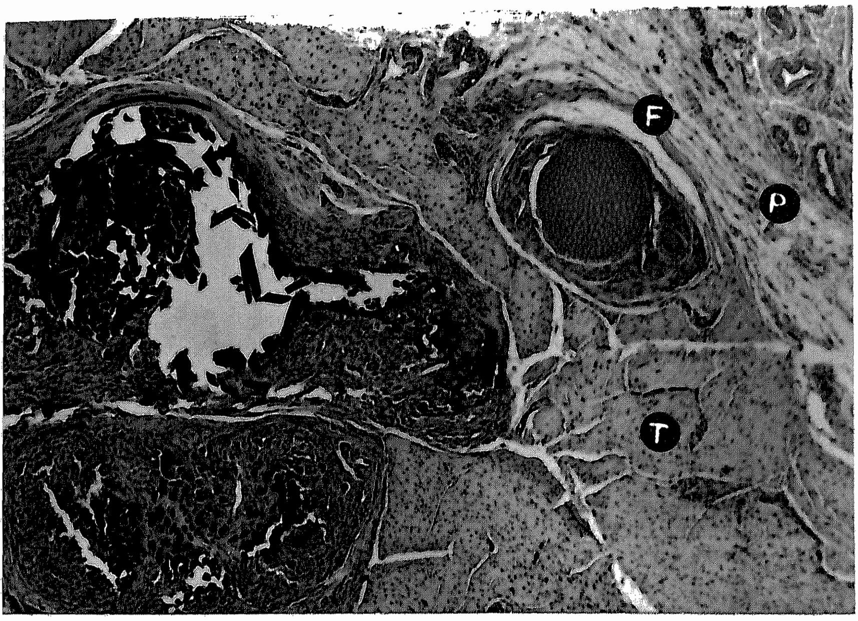


Fig. 91 Photomicrograph of a transverse section of the flexor digitorum profundus tendon of the right middle finger of monkey G.I. (Control).
Haematoxylin and Eosin X 120

This section was taken in the region of the suture line. There is a marked inflammatory reaction in relation to the suture material. The tendon (T) is adherent to the peritendinous tissues (P), there being no evidence of a sheath space.
Note the presence of a foreign body (F) which was thought to be a thorn, surrounded by a zone of reaction.

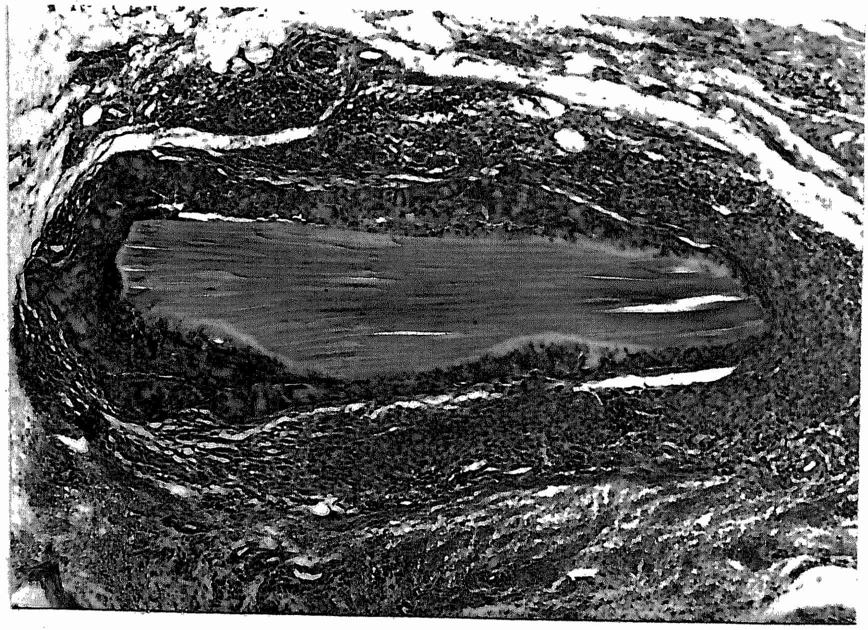


Fig. 92 High power photomicrograph of a longitudinal section of the thorn and surrounding reaction shown in Fig. 91.
Haematoxylin and Eosin X 120

Foreign bodies of this type were frequently found both macroscopically and microscopically.

Fig. 93 Photomicrograph of longitudinal section of flexor digitorum profundus tendon of the middle finger of monkey G.L. (Control).
Haematoxylin and Eosin X 70

The peritendinous tissues are adherent to the tendon. Note the well demarcated granulomatous reaction in relation to the suture material on the surface of the tendon.

## (6) THE RESULTS OF THE CONTROLLED EXPERIMENT

Monkey No: G.I

Date: 27.6.50

Sex: Male

Weight: 9½ lbs.

Anaesthetic: Nembutal 1.75 ccs. injected into the left lesser saphenous vein.

Pre-operative Recordings of Flexion: (Table 8).

| DIGIT | NEUTRAL POSITION | MAXIMAL FLEXION | MAXIMAL FLEXION AGAINST RESISTANCE | RANGE OF FLEXION |
|---|---|---|---|---|
| RIGHT INDEX | 40° | 75° | 60° | 35° |
| RIGHT MIDDLE | 38° | 75° | 70° | 37° |

Table 8. The pre-operative recordings of flexion at the distal interphalangeal joints of the right index and middle fingers of monkey G.I. (Figs. 79 to 82). The range of flexion of the index and middle fingers was 35° and 37° respectively, that is, from the neutral or position of rest to the position of maximal flexion.

The Operation:

The operative procedure was the same as that described in the text. (Page 89). The venous graft ensheathed the flexor digitorum profundus tendon of the index finger only. The middle finger acted as the CONTROL.

Duration of Operation: 2½ hours.

Recovery from Anaesthesia: About 5 hours after completion of the operation.

Post-operative Progress:

| | |
|---|---|
| 28.6.50. | Animal subdued and apprehensive. Plaster cast showed evidence of attempted removal. |
| 29.6.50. | Animal apparently well. Ate its food with the unaffected hand only. |
| 8.7.50. | Plaster cast very tattered. |
| 15.7.50. | Slight flexion noted at wrist, due to crack in plaster cast. |

17.7.50. The animal had succeeded in removing the plaster cast. The index finger and middle finger were held straight. The period of immobilisation of the hand was about 20 days.

Repeated observations of the hand of the animal at regular intervals revealed active flexion at the metacarpophalangeal joints only, but little at the interphalangeal joints.

Post-operative Recordings of Flexion: (Table 9).

Date: 21.3.51. - 267 days post-operatively.

Weight: 9¼ lbs. The animal had thus lost ¼ lb. in weight, but its general appearance was healthy.

Anaesthetic: Nembutal 1.25 ccs. was injected into the right lesser saphenous vein. The left lesser saphenous vein was thin and cord like, the result of thrombosis due to the previous injection of Nembutal.

Observations: The skin incision in the neck had healed well, leaving a thin linear scar. The finger incisions were inconspicuous. The pulp of the terminal phalanx of the right index finger was atrophic. Although both digits were held in extension the metacarpophalangeal and interphalangeal joints had an excellent range of passive movement.

| DIGIT | NEUTRAL POSITION | MAXIMAL FLEXION | MAXIMAL FLEXION AGAINST RESISTANCE | RANGE OF FLEXION. |
|---|---|---|---|---|
| RIGHT INDEX (Venous graft) | 10° | 11° | 10° | 1° |
| RIGHT MIDDLE (Control) | 29° | 40° | 23° | 11° |

Table 9. The post-operative recordings of flexion at the distal interphalangeal joints of the right index and middle fingers of monkey G.I. (Figs. 83 to 86). The range of flexion of the distal interphalangeal joints of the index and middle fingers was 1° and 11° respectively.

Both digits were then amputated through their respective metacarpophalangeal joints and prepared for histological section.

## The Functional Results (Monkey G.1).

### (a) The Venous graft (Index finger)

The pre-operative range of flexion of the distal interphalangeal joint of the index finger was 35°. 267 days after placing the venous graft around the sutured tendon, the range of flexion was 1°. Therefore the post-operative range of flexion was 2.9% of the normal.

### (b) The Control (Middle finger)

The pre-operative range of flexion of the distal interphalangeal joint of the middle finger was 37°. 267 days after tendon suture without using a venous graft the range of flexion was 11°. Therefore the post-operative range of flexion was 29.8% of the normal.

## The Histological Findings (Monkey G.1).

### Right Index Finger (Venous graft)

In the longitudinal sections the flexor digitorum profundus tendon could be seen from the base of the proximal phalanx to its insertion into the base of the distal phalanx. In the region of the base of the middle phalanx, the tendon was increased in diameter and contained jet black strands of suture material which had been sectioned longitudinally, transversely, and obliquely. Surrounding the suture material there was a well marked chronic inflammatory reaction consisting of small round cells, plasma cells and multinucleated giant cells. (Figs. 87 and 88). The tendon fibres were on the whole longitudinally aligned, but in the region of the suture material they were irregularly disposed and the tendon was very cellular. There was well marked proliferation of the intratendinous and peritendinous connective tissues with increased vascularity. (Fig. 87). No definite evidence of a tendon sheath was evident in the region of the suture line.

With specific staining, the venous graft was recognised by its elastic laminae and could be seen extending from the middle of the proximal phalanx to the distal third of the middle phalanx. (Figs. 89 and 90). There was no evidence of muscle fibres. Except in the region of the proximal portion of the venous graft, there was no suggestion of a cleavage line, the vein being intimately adherent to the tendon. In the region of the suture material, the adhesions were fairly dense and fibrous.

Right Middle Finger (Control)

In the longitudinal sections the digital portion of the tendon could be seen from the proximal phalanx to its insertion into the distal phalanx. The tendon in the region of the suture line was increased in diameter to about twice the size of the normal tendon and contained numerous strands of black suture material. Surrounding the suture material there was a well marked chronic inflammatory process consisting of small round cells, reticulum cells and multinucleated giant cells. (Figs. 91 and 93). The tendon fibres and cells were on the whole longitudinally aligned, but in the region of the suture material they were irregularly disposed. Tendon cellularity was not as marked as in the tendon of the index finger (venous graft). The intratendinous and peritendinous connective tissues were hypertrophied and vascular and numerous adhesions surrounded the tendon in the region of the suture line. The histology of the proximal and distal stumps was normal, and except at the insertion of the tendon there was no evidence of a tendon sheath.

During the course of the operations, foreign bodies, measuring about 3 mm's. in length, .5 mm. in width and tapering at one end, were occasionally noted in the subcutaneous tissues of the digits and even within the tendon sheaths. Histologically (Figs. 91 and 92) they were surrounded by a foreign body reaction consisting of numerous giant cells and small round cells.

These foreign bodies had the structure of vegetable matter and were probably fragments of thorns acquired by the animals in their natural environment.

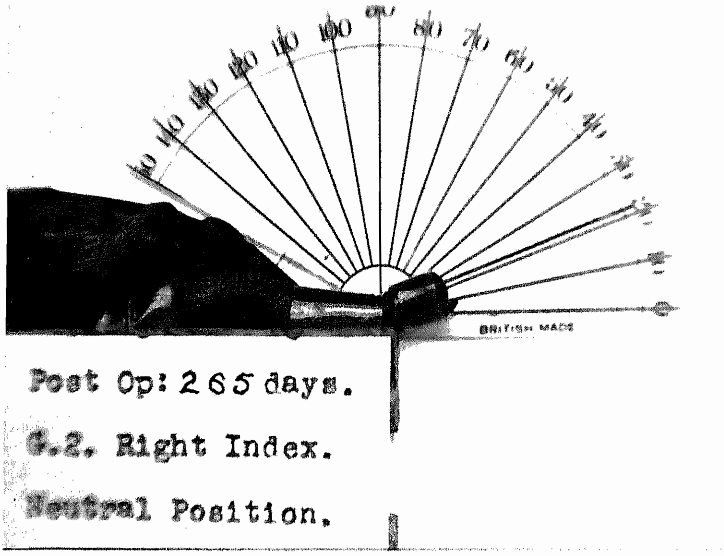


Fig. 94 Photograph of the right index finger (venous graft) of monkey G.2. in the Neutral Position, 265 days post-operatively.
Photographic reading - 22°
Corrected reading - 22°

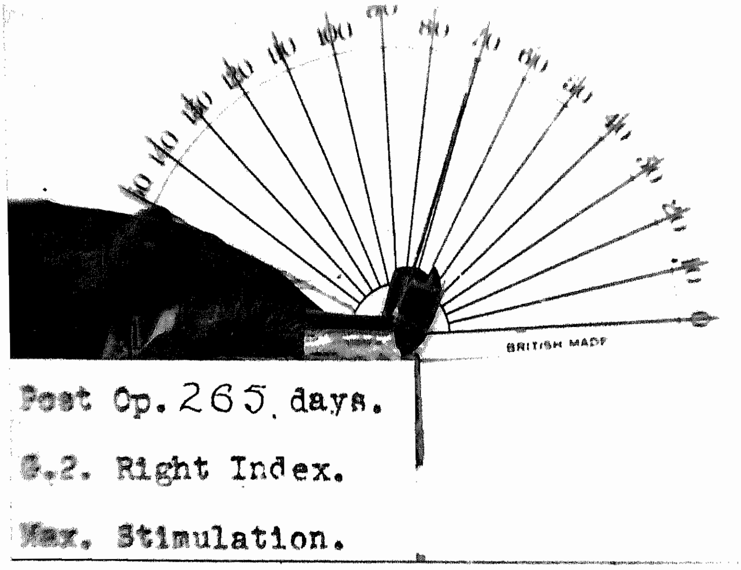


Fig. 95 Photograph of the right index finger (venous graft) of monkey G.2. in Maximal Flexion, 265 days post-operatively.
Photographic reading - 70°
Corrected reading - 70°

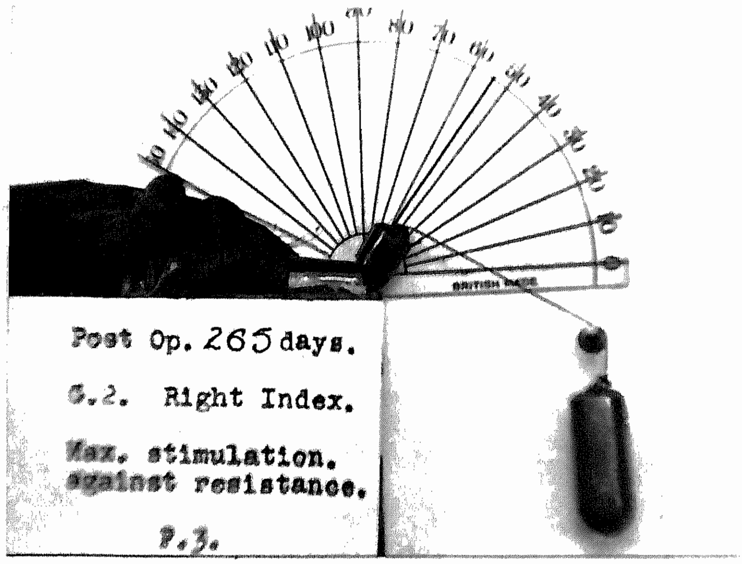


Fig. 96 Photograph of the right index finger (venous graft) of monkey G.2. in Maximal Flexion and against resistance, 265 days post-operatively.

Photographic reading - 55°

Corrected reading - 55°

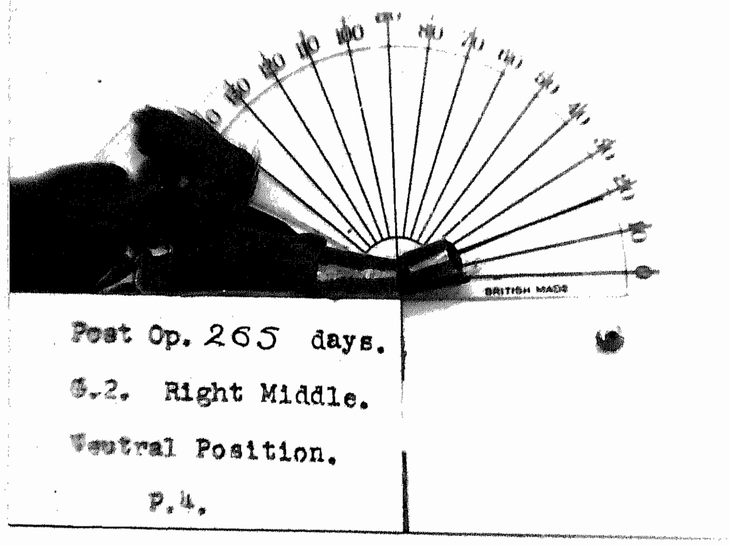


Fig. 97 Photograph of the right middle finger (Control) of monkey G.2. in the Neutral Position, 265 days post-operatively.

Photographic reading - 20°

Corrected reading - 20°

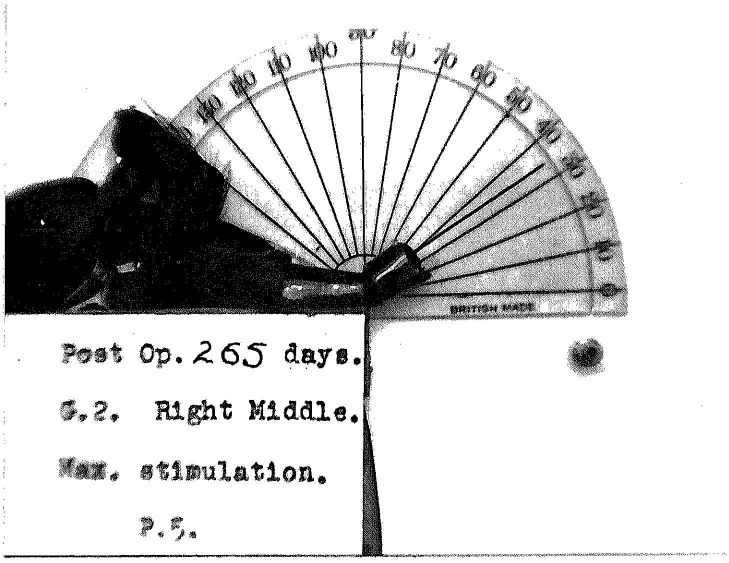


Fig. 98 Photograph of the right middle finger (Control) of monkey G.2. in Maximal Flexion, 265 days post-operatively.
Photographic reading - 35°
Corrected reading - 40°

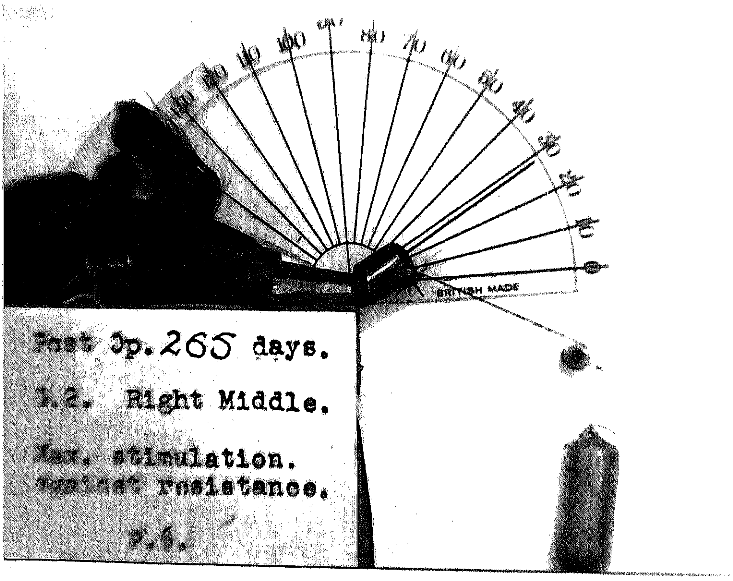


Fig. 99 Photograph of the right middle finger (Control) of monkey G.2. in Maximal Flexion and against resistance, 265 days post-operatively.
Photographic reading - 28°
Corrected reading - 28°

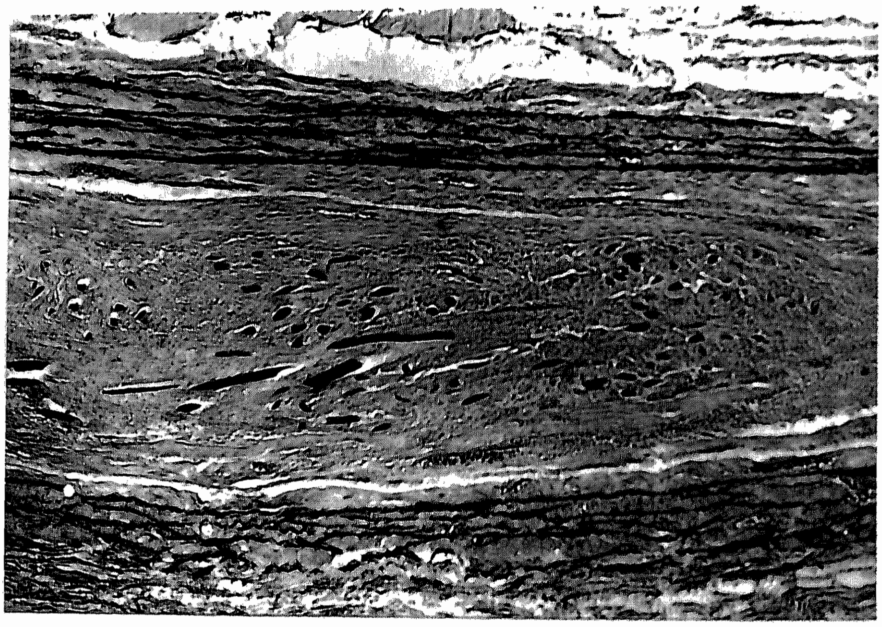


Fig. 100 Photomicrograph of a longitudinal section of the venous graft surrounding the flexor digitorum profundus tendon in the index finger of monkey G.2.

Weigert X 80

Note the suture material within the tendon and the elastic laminae of the venous graft.

Fig. 101 Photomicrograph of a longitudinal section of the flexor digitorum profundus tendon to show the termination of the venous graft

Weigert X 80

This section clearly illustrates the termination of the venous graft. Note that the tendon is adherent to the proximal phalanx. No sheath space is evident.

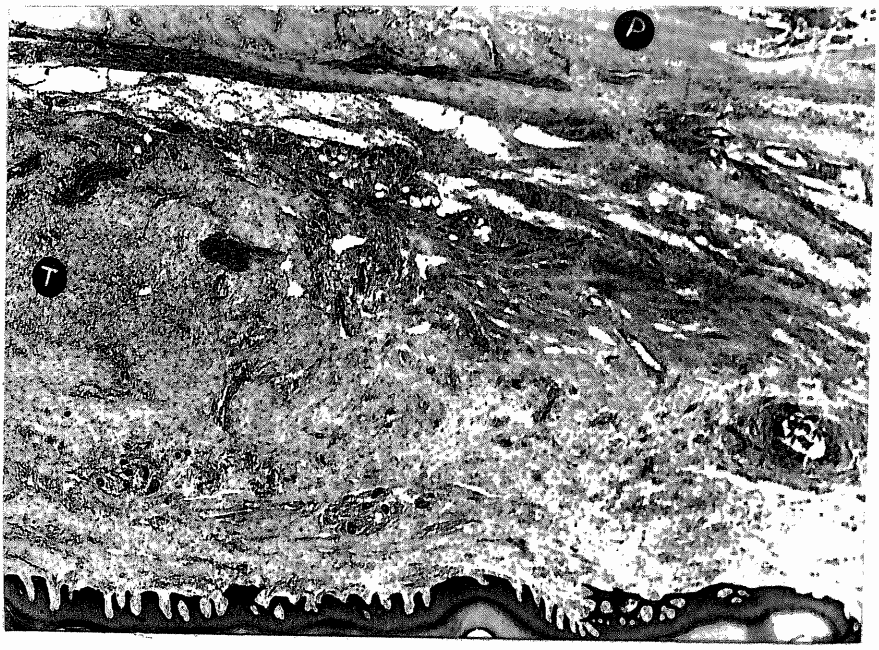


Fig. 102 Photomicrograph of a longitudinal section of the flexor digitorum profundus tendon of the middle finger of monkey G.2. in the region of tendon suture.

Haematoxylin and Eosin X 30

The tendon (T) is vascular, its fibres irregularly disposed and replaced in part by fibrous tissue containing numerous small round cells. Note that the tendon is intimately adherent to the subcutaneous tissues and to the phalanx (P).

Monkey No: G.2

Date: 6.7.50.

Sex: Male

Weight: 8 lbs.

Anaesthetic: Nembutal 1.25 ccs., injected into the right lesser saphenous vein.

Pre-operative Recordings of Flexion: (Table 10).

| DIGIT | NEUTRAL POSITION | MAXIMAL FLEXION | MAXIMAL FLEXION AGAINST RESISTANCE | RANGE OF FLEXION |
|---|---|---|---|---|
| RIGHT INDEX | 30° | 93° | 79° | 63° |
| RIGHT MIDDLE | 35° | 60° | 48° | 25° |

Table 10. The pre-operative recordings of flexion at the distal interphalangeal joints of the right index and middle fingers of Monkey G.2. The range of flexion at the distal interphalangeal joints of the index and middle fingers was 63° and 25° respectively. (The pre-operative photographic films of the recordings were spoiled during processing and were therefore unsuitable for reproduction).

The Operation:

The operative procedure was the same as that described in the text. Difficulty was experienced in threading the venous graft over the tendon, and after several unsuccessful attempts, the venous graft was discarded owing to the trauma inflicted upon it. The reason for this difficulty was the presence of a valve which was noted on exposing its lumen. A fresh venous graft was then removed from the right side of the neck. Two hours after the commencement of the operation, the animal showed signs of regaining consciousness. Consequently a further .75 cc. Nembutal was given intravenously.

Duration of Operation: $3\frac{1}{4}$ hours.

Post-operative Progress:

7.7.50. Animal well.

9.7.50. Plaster cast showed evidence of attempted removal.

6.8.50. As the plaster cast was still intact after a month, it was removed under anaesthesia (Nembutal I cc. intravenously). The skin incision on the index finger had healed well. A small discharging sinus was present at the proximal end of the skin incision of the middle finger.

20.8.50. A small degree of active movement was noted in the index finger but none in the middle finger.

Post-operative Recordings of Flexion: (Table II).

Date: 28.3.51. - 265 days post-operatively.

Weight: 8 lbs. 3 ozs. General appearance healthy. The animal had thus gained 3 ozs.

Anaesthetic: Nembutal 1.75 ccs. injected into left lesser saphenous vein.

Observations: There was no evidence of a scar on the index finger, but slight scarring was present on the middle finger at the site of the original skin incision. Good passive flexion was obtained at the interphalangeal joints of both fingers.

| DIGIT | NEUTRAL POSITION | MAXIMAL FLEXION | MAXIMAL FLEXION AGAINST RESISTANCE | RANGE OF FLEXION |
|---|---|---|---|---|
| RIGHT INDEX (Venous graft) | 22° | 70° | 55° | 48° |
| RIGHT MIDDLE (Control) | 20° | 40° | 28° | 20° |

Table II. The post-operative recordings of flexion at the distal interphalangeal joints of the right index and middle fingers of monkey G.2. (Figs. 94 to 99). The range of flexion of the distal interphalangeal joints of the index and middle fingers was 48° and 20° respectively.

## The Functional Results (Monkey G.2).

### (a) The Venous graft (Index finger)

The pre-operative range of flexion of the distal interphalangeal joint of the index finger was 63°. 265 days after placing the venous graft around the sutured tendon, the range of flexion was 48°. Therefore the post-operative range of flexion was 76.2% of the normal.

### (b) The Control (Middle finger)

The pre-operative range of flexion of the distal interphalangeal joint of the middle finger was 25°. 265 days after tendon suture without using a venous graft the range of flexion was 20°. Therefore the post-operative range of flexion was 80% of the normal.

## The Histological Findings (Monkey G.2).

### Right Index Finger (Venous graft)

In the longitudinal sections, the digital portion of the flexor digitorum profundus tendon was visible in its entire length. At the site of suture, the tendon was smaller in diameter than the rest of the tendon and contained numerous foci of recent haemorrhage. The intratendinous and peritendinous connective tissues were increased in quantity. Except at the insertion of the tendon, no definite sheath space was seen. The tendon fibres in the region of the suture line showed a general tendency towards longitudinal alignment, but in the vicinity of the suture material the fibres were irregularly disposed. Well marked chronic inflammatory changes were noted in relation to the suture material. Proximal to the site of suture the elastic fibres of the venous graft were clearly visible (Figs. 100 and 101), but directly over the suture line the elastic fibres were disorganised, and the vein infiltrated with small round cells. The venous graft was adherent to the tendon in its entire length. No muscle fibres were evident in the wall of the vein.

Right Middle Finger (Control)

In the longitudinal sections, the digital portion of the flexor digitorum tendon was noted in its whole extent. At its insertion the normal tendon sheath was visible, and the tendon displayed normal cytology, but elsewhere the tendon was adherent to the peritendinous tissues. In the region of the suture line, the tendon fibres were scanty, irregularly disposed and separated by a loose, disorganised connective tissue, containing numerous blood vessels and foci of active inflammatory change. (Fig. 102). The maximum intensity of inflammatory reaction was noted in relation to the suture material. At certain areas difficulty was experienced in distinguishing clearly tendon fibres from fibrous tissue.

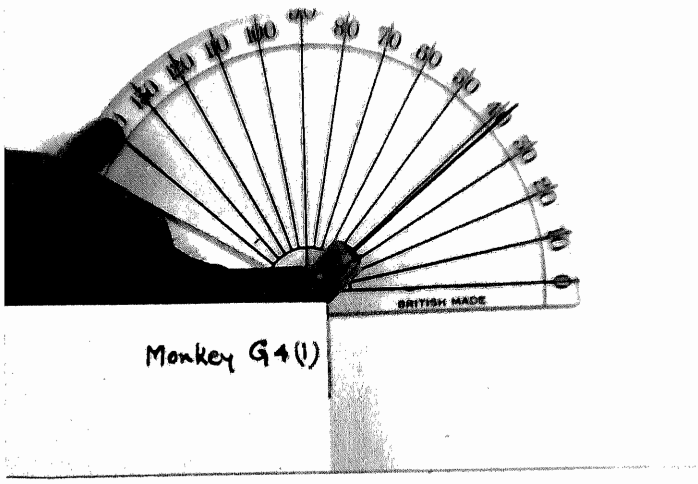


**Fig. 103** Photograph of the right index finger of monkey G.4. in the Neutral Position before the operation.

Photographic reading - 38°  
Corrected reading - 39°

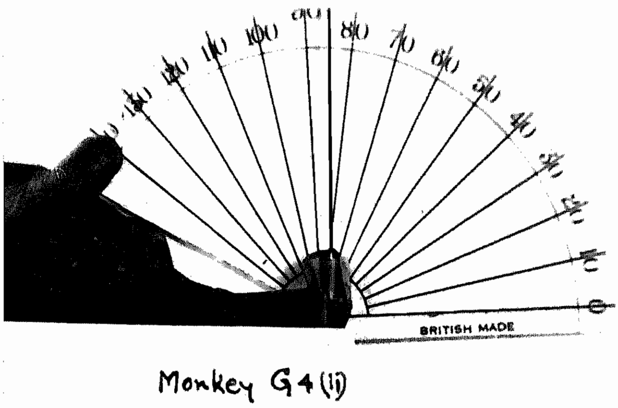


**Fig. 104** Photograph of the index finger of monkey G.4. in Maximal Flexion before the operation.

Photographic reading - 85°  
Corrected reading - 95°

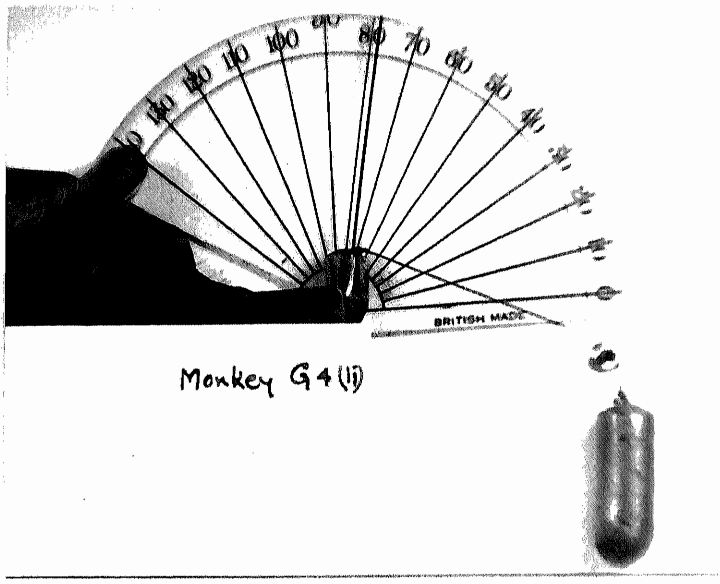


Fig. 105 Photograph of the index finger of monkey G.4. in Maximal Flexion against resistance before the operation

Photographic reading - 78°
Corrected reading - 88°

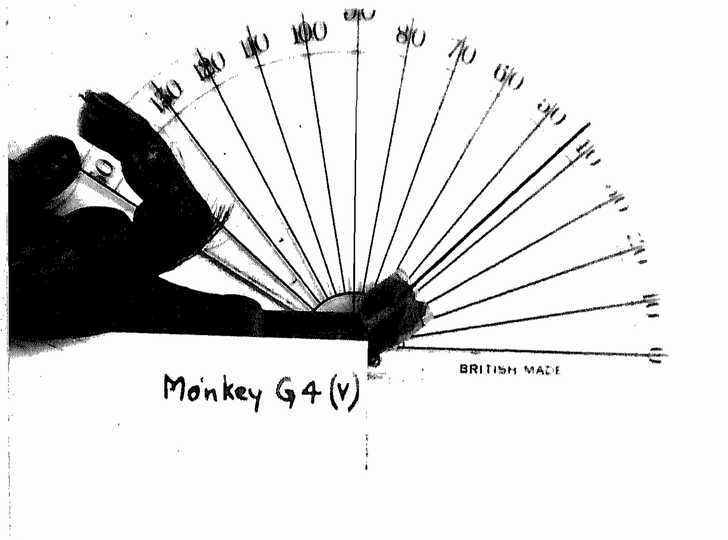


Fig. 106 Photograph of the middle finger of Monkey G.4. in Neutral Position before the operation.

Photographic reading - 44°
Corrected reading - 46°

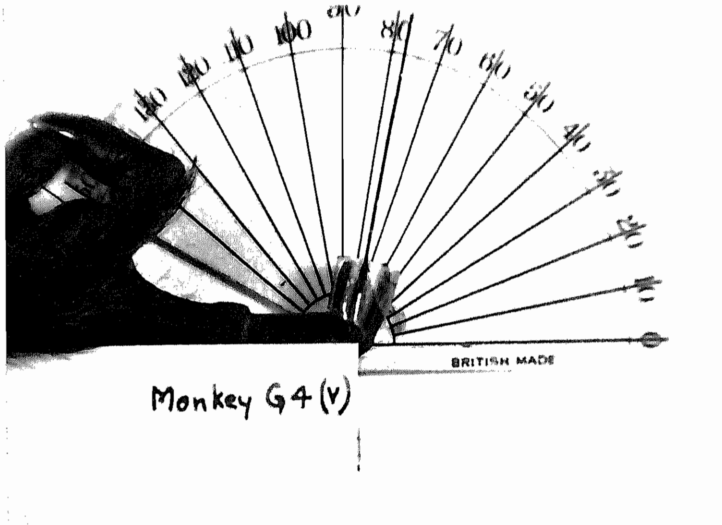


Fig. 107 Photograph of the middle finger of monkey G.4. in Maximal Flexion before the operation.
Photographic reading - 77°
Corrected reading - 70°

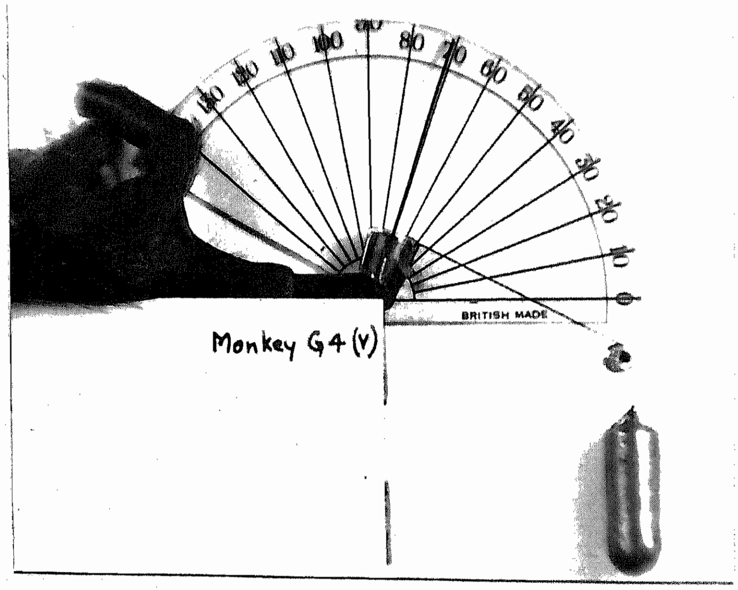


Fig. 108 Photograph of the middle finger of monkey G.4. in Maximal Flexion against resistance before the operation.
Photographic reading - 71°
Corrected reading - 66°

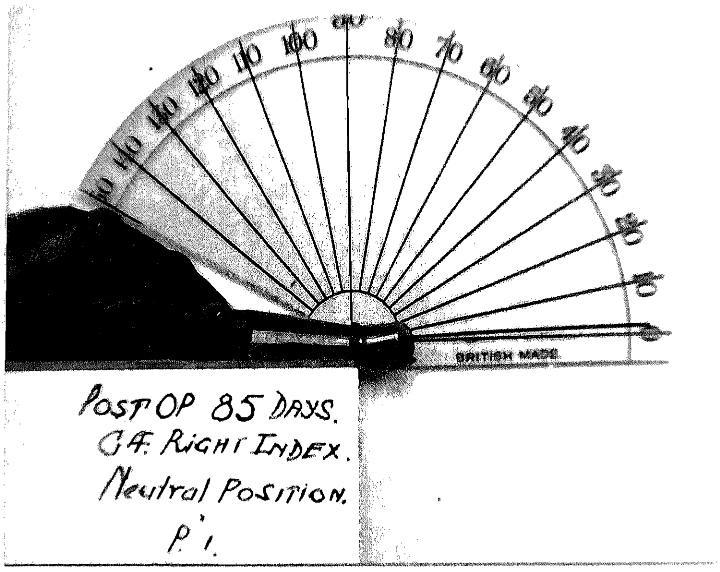


Fig. 109 Photograph of the right index finger of monkey G.4. (Venous graft) in the Neutral Position, 85 days post-operatively.
Photographic reading - 2°
Corrected reading - 4°

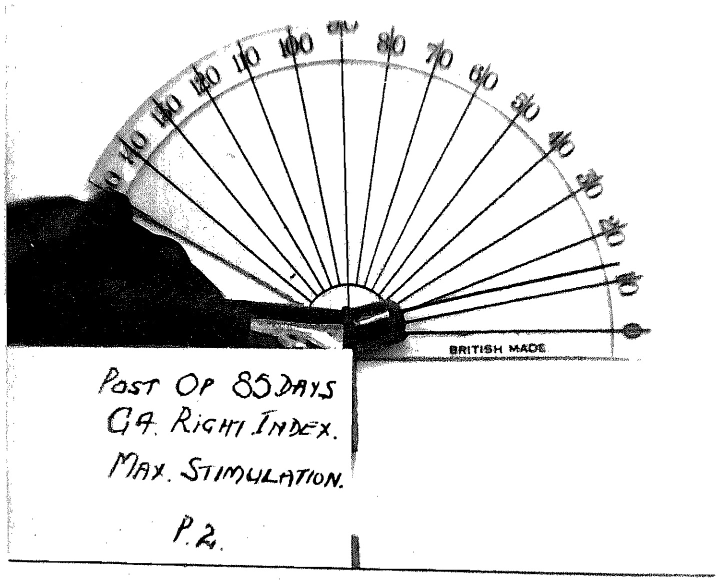


Fig. 110 Photograph of the right middle finger of monkey G.4. (venous graft) in Maximal Flexion, 85 days post-operatively.
Photographic reading - 14°
Corrected reading - 18°

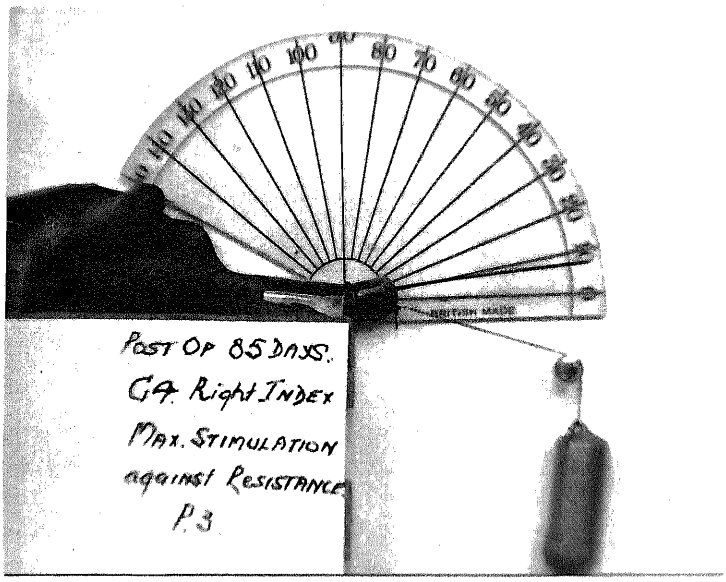


Fig. 111 Photograph of the right index finger of monkey G.4. (venous graft) in Maximal Flexion and against resistance, 85 days post-operatively.

Photographic reading - 8°
<u>Corrected reading</u> - 11°

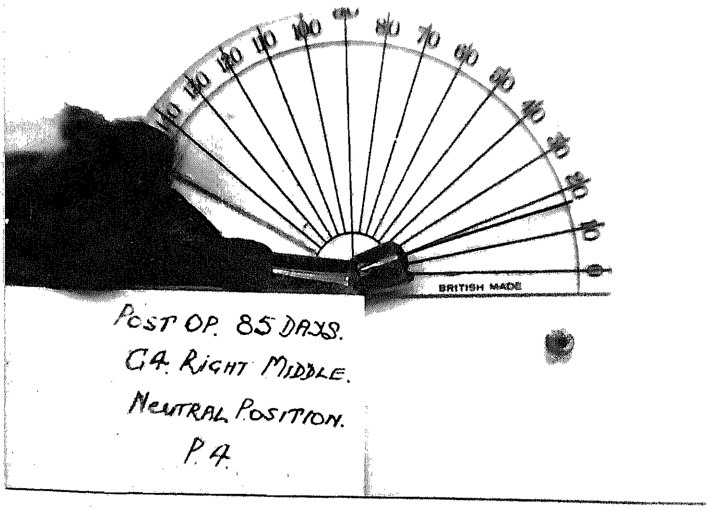


Fig. 112 Photograph of the right middle finger of monkey G.4. (Control) in the Neutral Position, 85 days post-operatively.

Photographic reading - 17°
<u>Corrected reading</u> - 23°

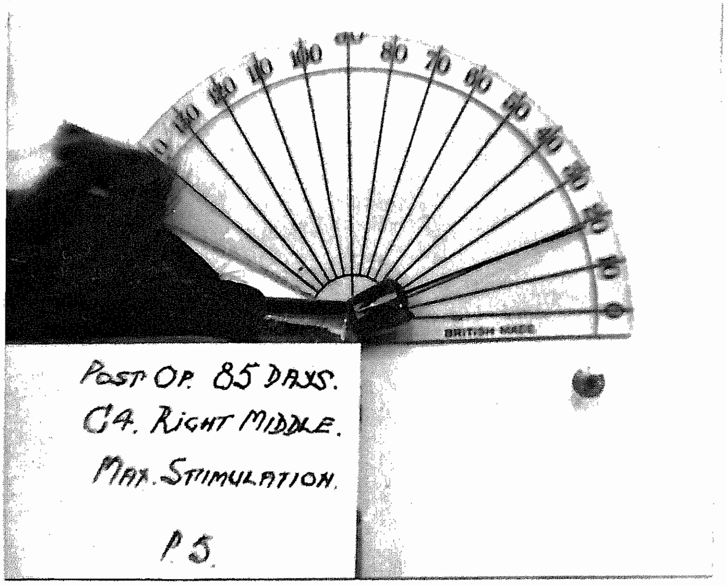


Fig. 113 Photograph of the right middle finger of monkey G.4. (Control) in Maximal Flexion 85 days post-operatively.
Photographic reading - 19°
Corrected reading - 30°

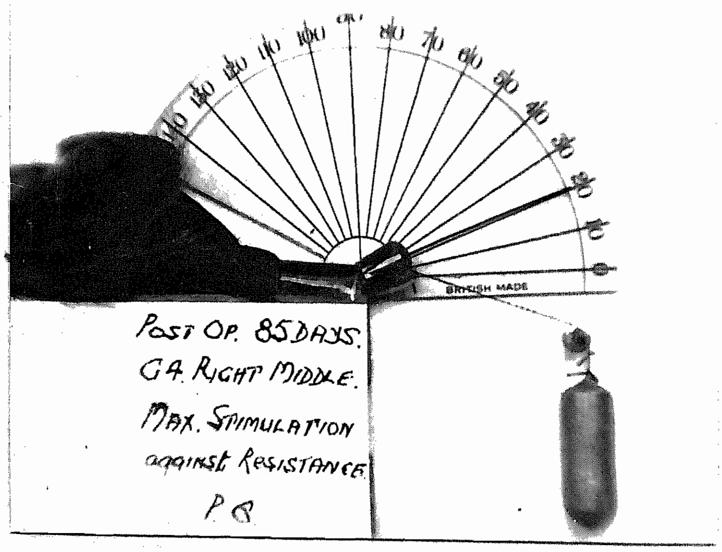


Fig. 114 Photograph of the right middle finger of monkey G.4. (Control) in Maximal Flexion, and against resistance 85 days post-operatively.
Photographic reading - 20°
Corrected reading - 24°

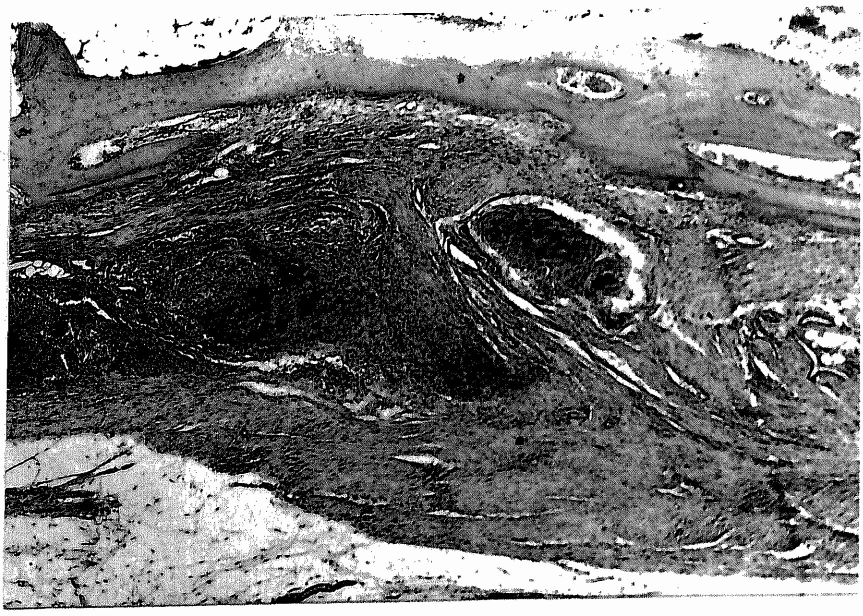


**Fig. 115** Photomicrograph of a longitudinal section of the flexor digitorum profundus tendon of the index finger of monkey G.4. (venous graft)
Haematoxylin and Eosin X 45

The site of tendon suture is bulbous, the tendon fibres are irregularly disposed and there is an increase of intratendinous connective tissue. There is no evidence of a sheath space; the tendon is adherent to the phalanx and the peritendinous connective tissues.

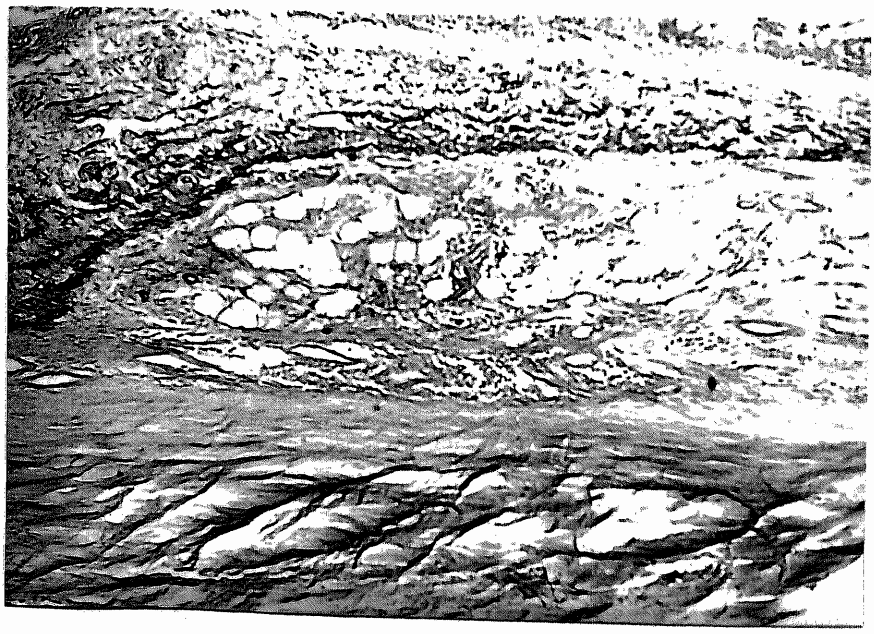


**Fig. 116** Photomicrograph of a longitudinal section of the flexor digitorum profundus tendon of the index finger of monkey G.4. to show the venous graft.

Weigert X 80

Note the elastic fibres of the venous graft, and the peritendinous connective tissue which is vascular and contains numerous fat cells. There is no evidence of a sheath space.

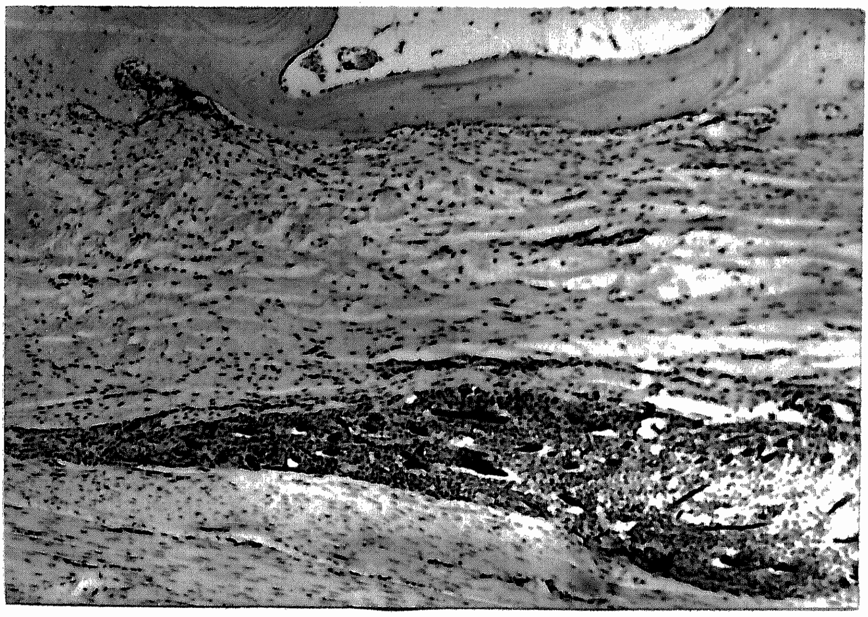


Fig. 117 Photomicrograph of a longitudinal section of the flexor digitorum profundus tendon of the middle finger of monkey G.4. (control).
Haematoxylin and Eosin X 70

Note the chronic inflammatory reaction in relation to the suture material and the adherence of the tendon to bone, Monkey No: G.4

Date: 5.1.51.

Sex: Male.

Weight: 9 lbs. 14 ozs.

Anaesthetic: Nembutal 1.75 ccs. injected into left lesser saphenous vein.

Pre-operative Recordings of Flexion: (Table 12).

| DIGIT | NEUTRAL POSITION | MAXIMAL FLEXION | MAXIMAL FLEXION AGAINST RESISTANCE | RANGE OF FLEXION |
|---|---|---|---|---|
| RIGHT INDEX | 39° | 95° | 88° | 56° |
| RIGHT MIDDLE | 46° | 70° | 66° | 24° |

Table 12. The pre-operative recordings of flexion at the distal interphalangeal joints of the right index and middle fingers of monkey G.4. (Figs. 103 to 108). The range of flexion at the distal interphalangeal joints of the index and middle fingers was 56° and 24° respectively.

The Operation: The operative procedure was the same as that described in the text. The venous graft ensheathed the flexor digitorum profundus tendon of the index finger only. The middle finger acted as the CONTROL.

Duration of Operation: 2¼ hours.

Recovery from Anaesthesia: About 4 hours after completion of the operation.

Post-operative Progress:

6.1.51. Animal apparently well.

7.1.51. Plaster cast was slightly tattered.

20.1.51. Plaster cast was still intact.

24.1.51. Complete removal of plaster cast by the animal.

29.1.51. No obvious active movements were noted in the affected fingers. The fingers were held in almost complete extension. The period of immobilisation of the hand was about 19 days.

Post-operative Recordings of Flexion: (Table 13).

Date: 30.3.51. - 85 days post-operatively.

Weight: 9 lbs. 2 ozs. The animal had lost 12 ozs. in weight but its general appearance was healthy.

Anaesthetic: Nembutal 1.5 ccs. injected into the right lesser saphenous vein.

Observations: The skin incisions had healed without visible scarring. The pulps of both fingers were atrophic and the skin shiny and depigmented. Passive flexion in both digits was poor.

| DIGIT | NEUTRAL POSITION | MAXIMAL FLEXION | MAXIMAL FLEXION AGAINST RESISTANCE | RANGE OF FLEXION |
|---|---|---|---|---|
| RIGHT INDEX (Venous Graft) | 4° | 18° | 11° | 14° |
| RIGHT MIDDLE (Control) | 23° | 30° | 24° | 7° |

Table 13. The post-operative recordings of flexion at the distal interphalangeal joints of the right index and middle fingers of monkey G.4. (Figs. 109 to 114). The range of flexion of the distal interphalangeal joints of the index and middle fingers was 14° and 7° respectively.

The Functional Results: (Monkey G.4).

(a) The Venous Graft (Index finger)

The pre-operative range of flexion of the distal interphalangeal joint of the index finger was 56°. 85 days after placing the venous graft around the sutured tendon, the range of flexion was 14°. Therefore the post-operative range of flexion was 25% of the normal.

(b) The Control (Middle finger).

The pre-operative range of flexion of the distal interphalangeal joint of the middle finger was 24°. 85 days after tendon suture without using a venous graft, the range of flexion was 7°. Therefore, the post-operative range of flexion was 29.1% of the normal.

The Histological Findings (Monkey G.4).

Right Index Finger (Venous graft)

The digital portion of the flexor digitorum tendon could be seen in its entire length, in the longitudinal sections. The histology of the proximal and distal stumps was normal but the site of tendon suture was occupied by vascular connective connective tissue containing scattered tendon cells and collagen fibres which were irregularly disposed. Well marked chronic inflammatory changes were noted in the intratendinous and peritendinous connective tissues. No sheath space was visible and the tendon was intimately adherent to the volar surface of the middle phalanx and interphalangeal joints. (Fig. 115). The special elastic stains revealed only portions of the venous graft (Fig. 116) in which the elastic laminae of the vein were scanty. No muscle fibres were evident in the wall of the vein, the substance of which was infiltrated by granulation tissue.

Right Middle Finger (Control)

In the longitudinal sections, the digital portion of the flexor digitorum profundus tendon was evident in its entire extent.

In the region of the suture line the tendon fibres were scant, irregularly disposed, and the junction composed mainly of fibrous tissue. The intratendinous connective tissues were hypertrophied and contained numerous blood vessels and foci of chronic inflammatory reaction. Except at the insertion of the tendon, no definite sheath space was visible, the tendon being adherent to surrounding structures. (Fig. 117).

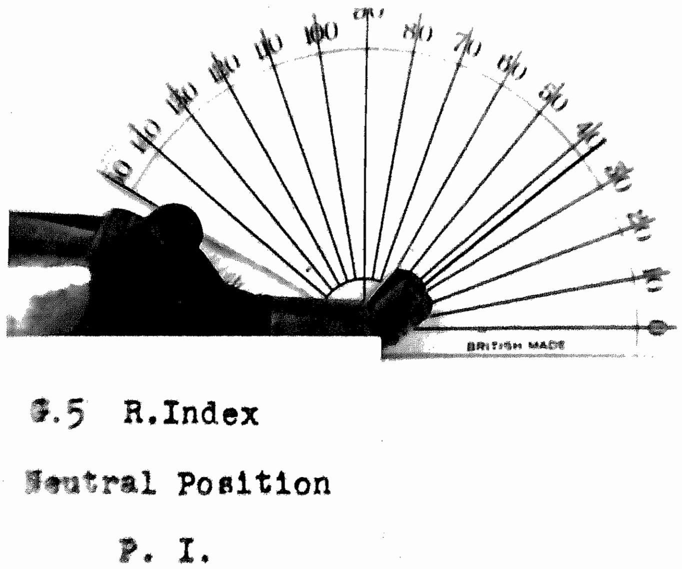


**Fig. 118** Photograph of the right index finger of monkey G.5. in the Neutral Position before the operation.

Photographic reading - 37°
Corrected reading - 37°

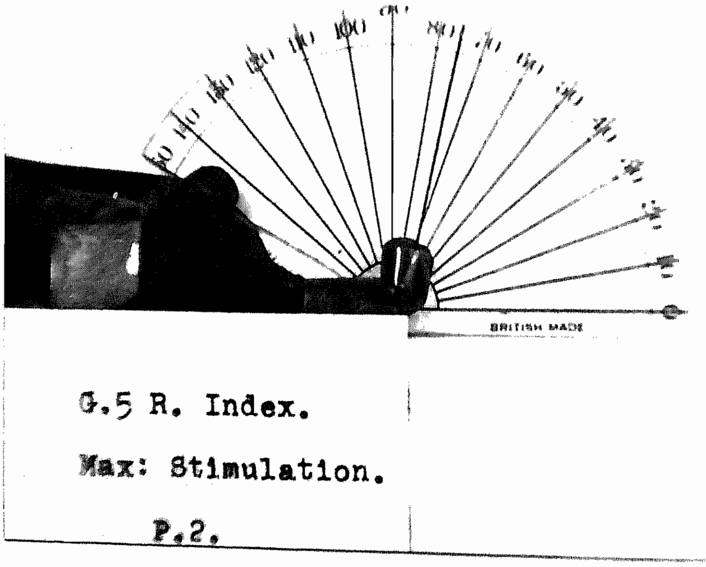


**Fig. 119** Photograph of the right index finger of monkey G.5. in Maximal Flexion before the operation.

Photographic reading - 75°
Corrected reading - 85°

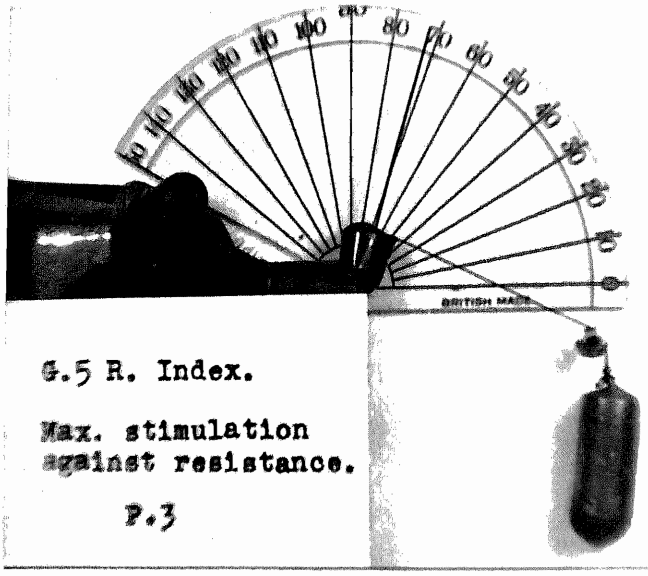


Fig. 120 Photograph of the right index finger of monkey G.5. in Maximal Flexion and against resistance before the operation.
Photographic reading - 73°
Corrected reading - 75°

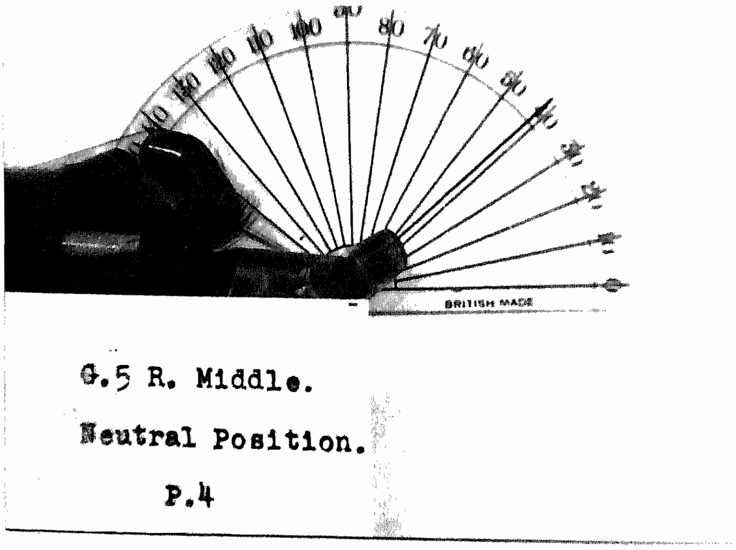


Fig. 121 Photograph of the right middle finger of monkey G.5. in the Neutral Position before the operation.
Photographic reading - 42°
Corrected reading - 33°

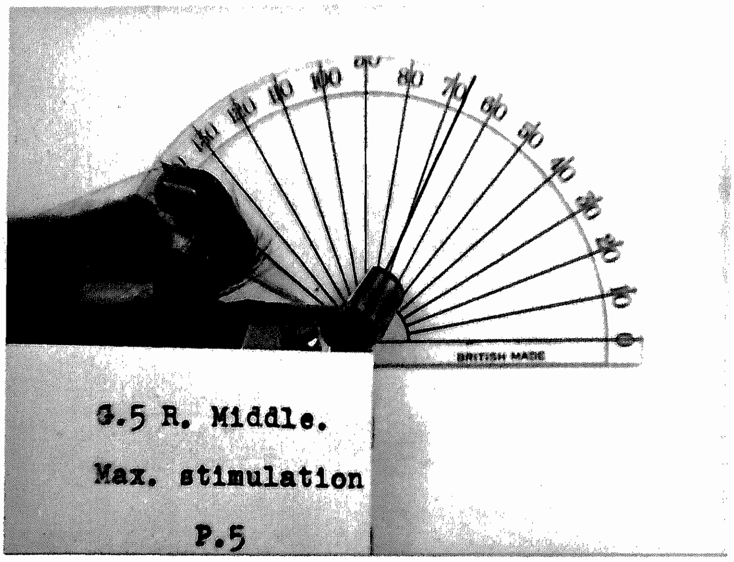


Fig. 122 Photograph of the right middle finger of monkey G.5. in Maximal Flexion before the operation.

Photographic reading - 67°
<u>Corrected reading</u> - 58°

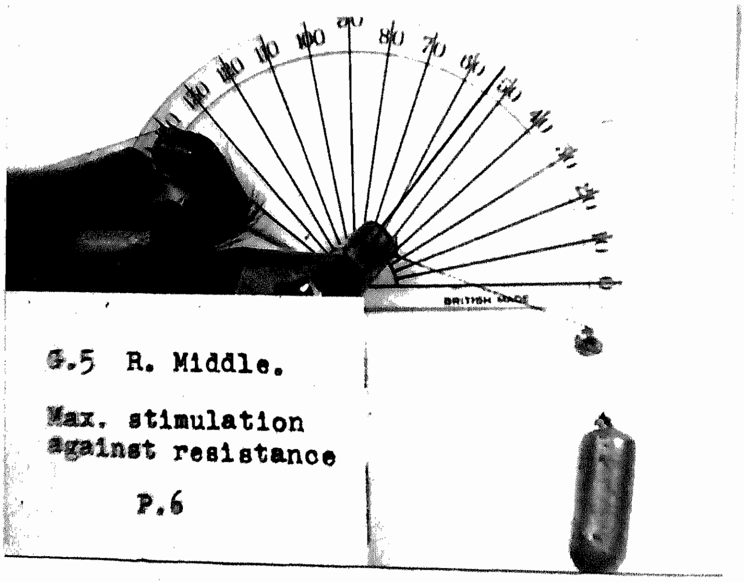


Fig. 123 Photograph of the right middle finger of monkey G.5. in Maximal Flexion and against resistance before the operation.

Photographic reading - 54°
<u>Corrected reading</u> - 50°

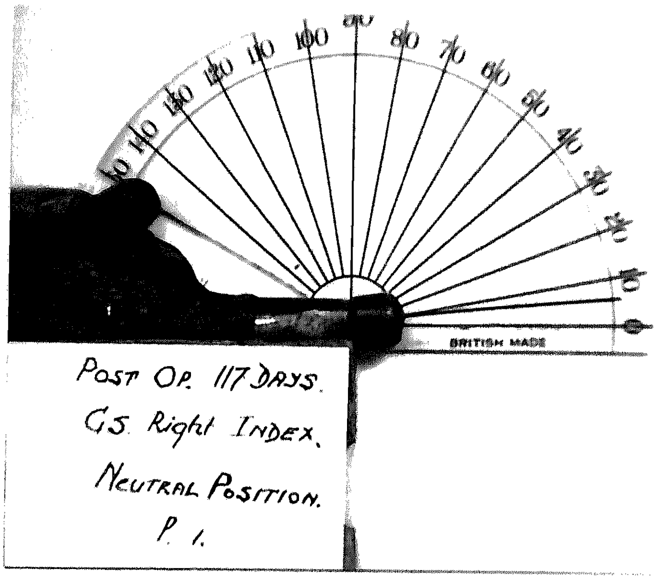


Fig. 124 Photograph of the right index finger of monkey G.5. (venous graft) in the Neutral Position 117 days post-operatively.

Photographic reading - 6°

Corrected reading - 6°

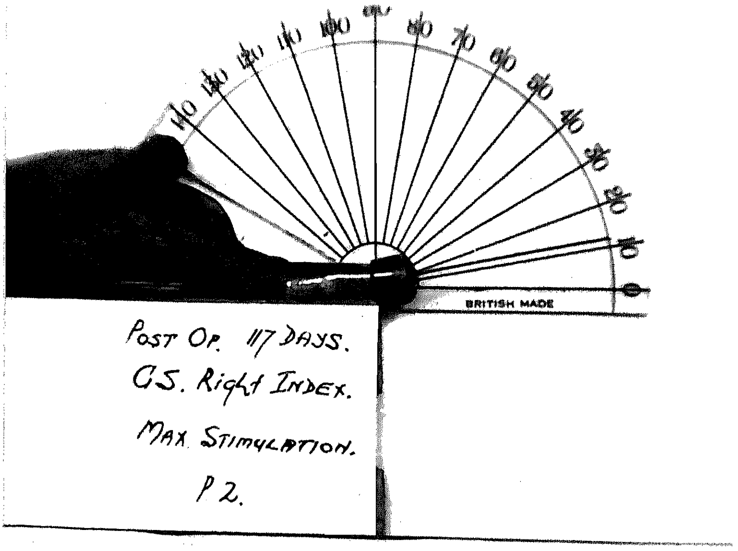


Fig. 125 Photograph of the right index finger of monkey G.5. (venous graft) in Maximal Flexion, 117 days post-operatively.

Photographic reading - 12°

Corrected reading - 12°

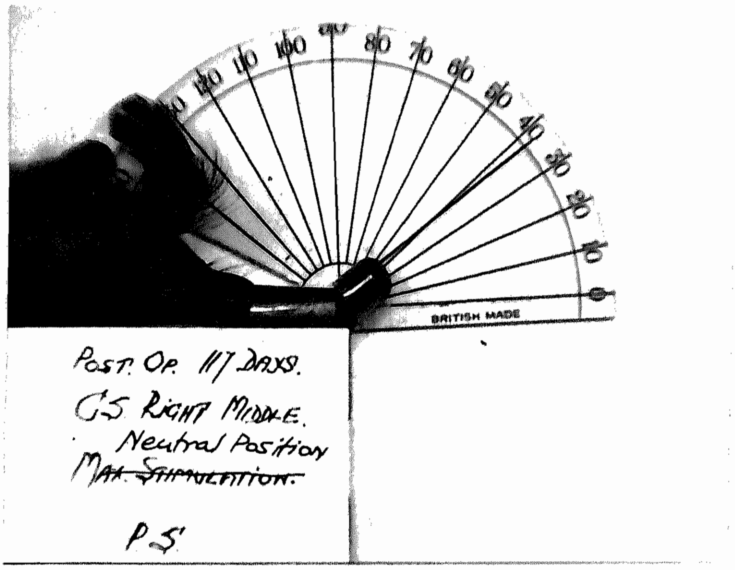


**Fig. 126** Photograph of the right middle finger (control) of monkey G.5. in the Neutral Position 117 days post-operatively.

Photographic reading - 38°
Corrected reading - 34°

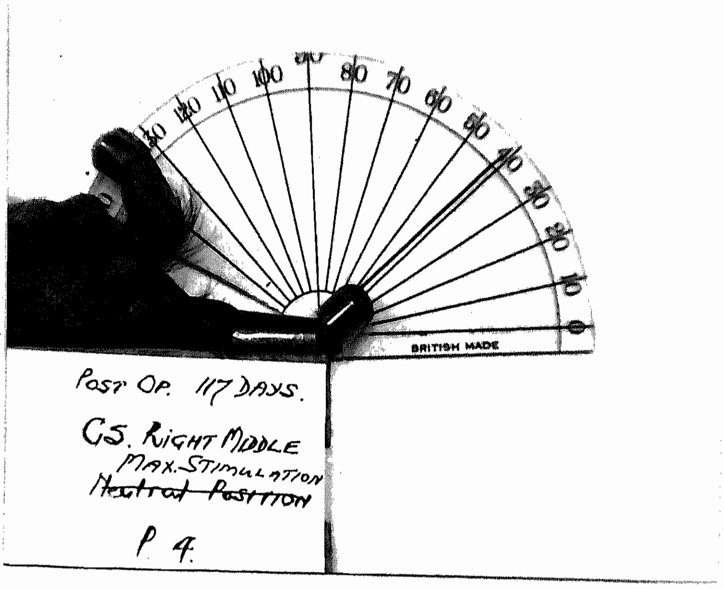
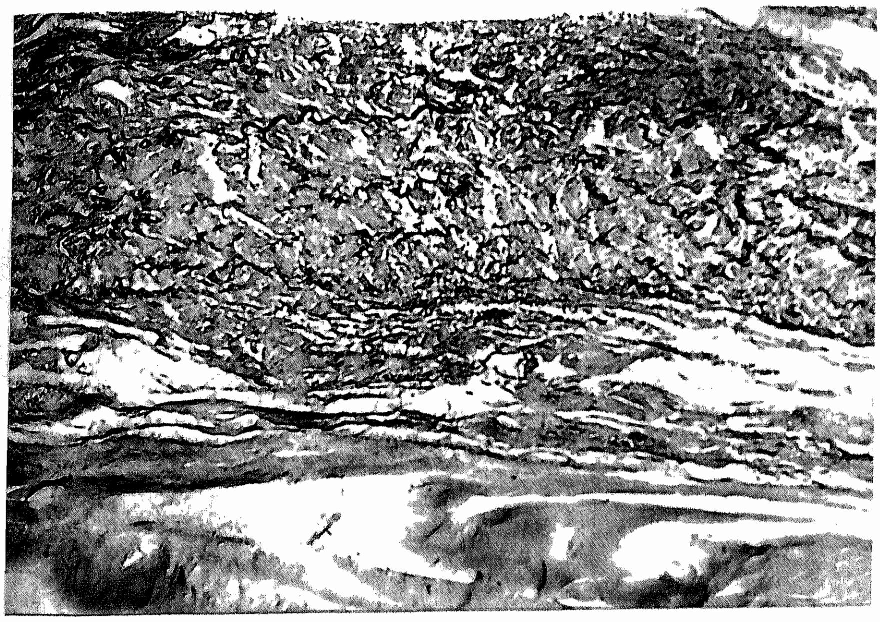


**Fig. 127** Photograph of the right middle finger (Control) of monkey G.5. in Maximal Flexion 117 days post-operatively.

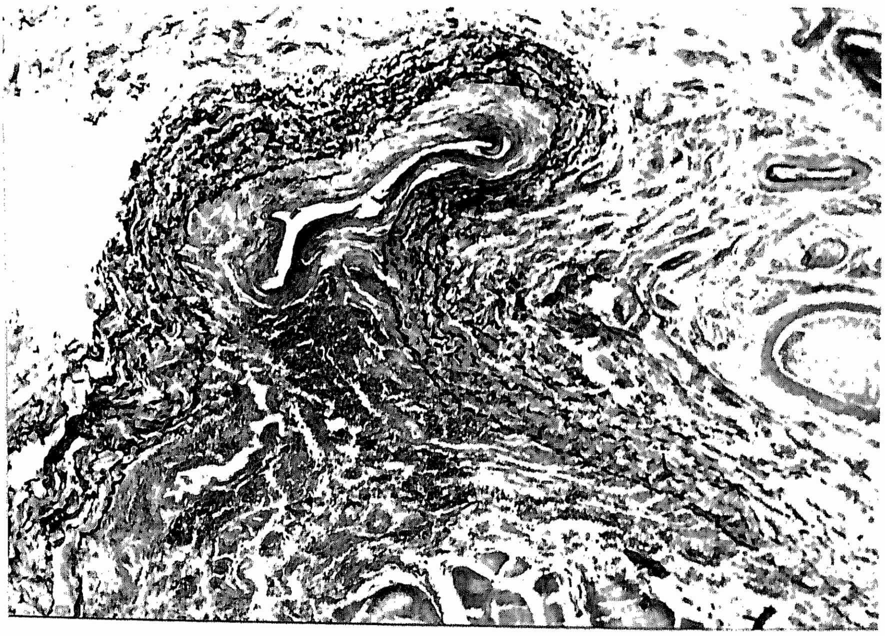
Photographic reading - 42°
Corrected reading - 46°



<u>Fig. 128</u> Photomicrograph of a longitudinal section of the venous graft in the index finger of monkey G.5.

Weigert X 130

Note the elastic fibres in the venous graft. The vein is adherent to the tendon. No sheath space is evident.



<u>Fig. 129</u> Photomicrograph of a transverse section of the venous graft in the index finger of monkey G.5.

Weigert X 130

Note the elastic fibres in the venous graft and the adhesions between the tendon and the vein.

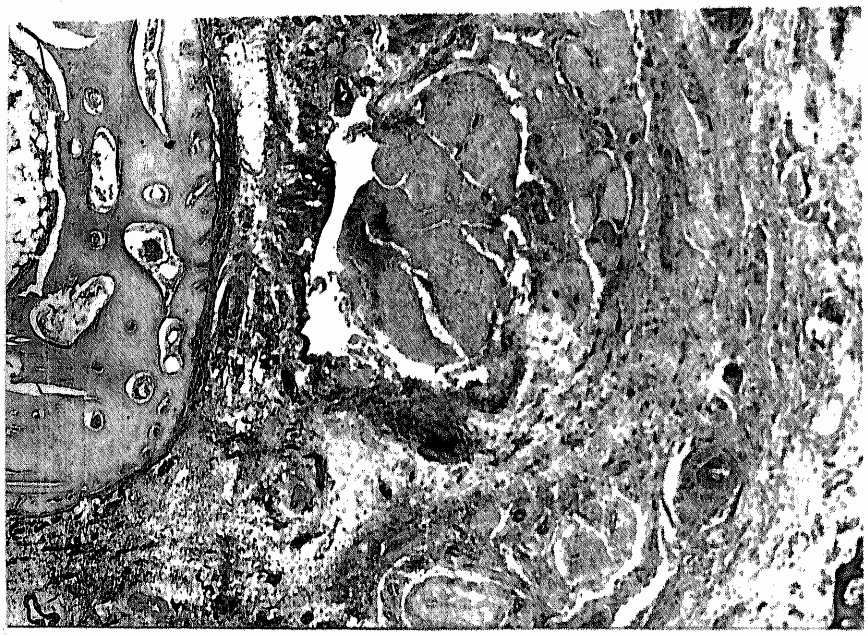


Fig. 130 Photomicrograph of a transverse section of the flexor digitorum profundus tendon of the middle finger (control) of monkey G.5. in the region of the suture line.
Haematoxylin and Eosin X 40

Note the increase in intratendinous connective tissue. No sheath space is visible.

**Monkey No:** G.5

**Date:** 11.1.51.

**Sex:** Male.

**Weight:** 11 lbs. 8 ozs.

**Anaesthetic:** Nembutal 2 ccs. injected into left lesser saphenous vein.

**Pre-operative Recordings of Flexion:** (Table 14)

| DIGIT | NEUTRAL POSITION | MAXIMAL FLEXION | MAXIMAL FLEXION AGAINST RESISTANCE | RANGE OF FLEXION |
|---|---|---|---|---|
| RIGHT INDEX | 37° | 85° | 75° | 48° |
| RIGHT MIDDLE | 33° | 58° | 50° | 25° |

Table 14. The pre-operative recordings of flexion at the distal interphalangeal joints of the right index and middle fingers of monkey G.5. (Figs. 118 to 123). The range of flexion at the distal interphalangeal joints of the index and middle fingers was 48° and 25° respectively.

**The Operation:** The operative procedure was the same as that described in the text, the venous graft ensheathing the flexor digitorum profundus tendon of the index finger only. The middle finger acted as the CONTROL. The external jugular vein could not be found, consequently a segment of the internal jugular vein was used.

**Duration of Operation:** 2¼ hours.

**Recovery from Anaesthesia:** About 1 hour after the operation.

**Post-operative Progress:**

12.1.51. Animal outwardly well.

18.1.51. Plaster cast slightly tattered at edges.

27.1.51. Plaster cast still intact at wrist.

31.1.51. The plaster cast had been completely removed by animal. The fingers were held in the extended position. No obvious active flexion noted in the interphalangeal joints.

10.2.51. No active flexion observed.

23.2.51. No active flexion observed.

16.3.51. Fingers still held in extension. No obvious flexion noted. The period of immobilisation of the hand was about 20 days.

Post-operative Recordings of Flexion: (Table 15).

Date: 8.5.51. - 117 days post-operatively.

Weight: 11 lbs. The animal had therefore lost 8 ozs. in weight. Its general appearance was healthy however.

Anaesthetic: Nembutal 1.75 ccs. into the left lesser saphenous vein.

Observations: There was no visible evidence of the original skin incisions. The interphalangeal joints of the affected fingers were held in extension. The pulps of the fingers were atrophied and the overlying skin depigmented and shiny.

| DIGIT | NEUTRAL POSITION | MAXIMAL FLEXION | MAXIMAL FLEXION AGAINST RESISTANCE | RANGE OF FLEXION |
|---|---|---|---|---|
| RIGHT INDEX (Venous graft) | 6° | 12° | Not recorded | 6° |
| RIGHT MIDDLE (Control) | 34° | 46° | Not recorded | 12° |

Table 15. The post-operative recordings of flexion at the distal interphalangeal joints of the right index and middle fingers of monkey G.5. (Figs. 124 to 127). The range of flexion of the distal interphalangeal joints of the index and middle fingers was 6° and 12° respectively.

The Functional Results (Monkey G.5).

(a) The Venous graft (Index finger)

The pre-operative range of flexion of the distal interphalangeal joint of the index finger was 48°. 117 days after placing the venous graft around the sutured tendon, the range of flexion was 6°. Therefore, the post-operative range of flexion was 12.5% of the normal.

(b) <u>The Control</u> (Middle finger)

The pre-operative range of flexion of the distal interphalangeal joint of the middle finger was 25°. 117 days after tendon suture without using a venous graft, the range of flexion was 12°. Therefore, the post-operative range of flexion was <u>48.0% of the normal</u>.

<u>The Histological Findings</u> (Monkey G.5).

<u>Right Index Finger</u> (Venous graft)

The region of the suture line was characterised by fibro-vascular tissue in which few tendon fibres were evident. Except at the insertion of the tendon, no sheath space was visible, the tendon being adherent to the peritendinous connective tissues throughout its digital course. With the special elastic stains, the venous graft was evident. (Figs. 128 and 129). No muscle fibres were noted, and the wall of the vein was infiltrated by granulation tissue containing foci of foreign body reaction.

<u>Right Middle Finger</u> (Control)

The longitudinal sections were not entirely suitable for study as the tendon was sectioned obliquely and superficially. The only portion of the tendon visible in the longitudinal sections was in the region of its insertion where the cytology was normal. In the transverse sections, the region of the suture line revealed a marked increase in the intratendinous connective tissues with dense adhesions uniting the tendon to the peritendinous connective tissues. (Fig. 130).

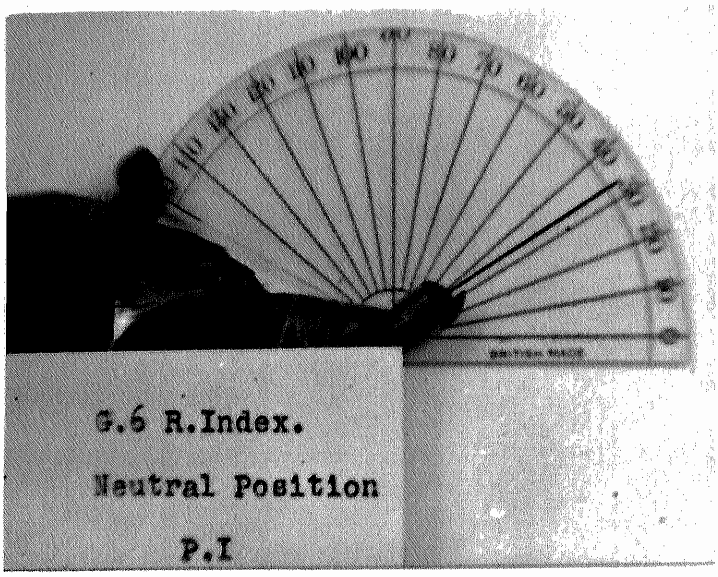


**Fig. 132** Photograph of the right index finger of monkey G.6. in the Neutral Position before the operation.

Photographic reading - 34°
<u>Corrected reading</u> - 34°

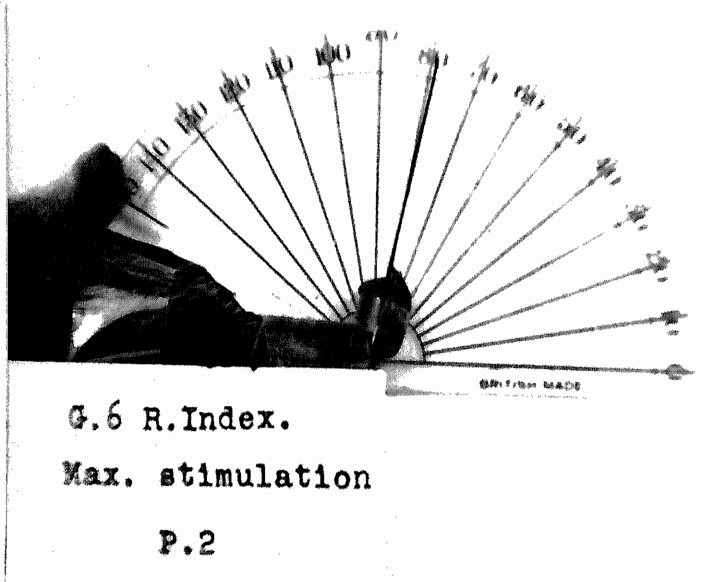


**Fig. 133** Photograph of the right index finger of monkey G.6. in Maximal Flexion before the operation.

Photographic reading - 79°
<u>Corrected reading</u> - 76°

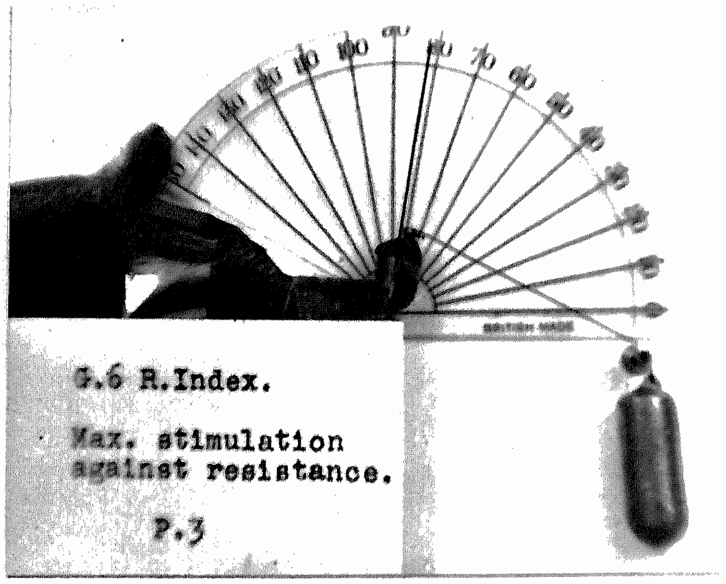


**Fig. 134** Photograph of the right index finger of monkey G.6. in Maximal Flexion and against resistance before the operation.
Photographic reading - 82°
Corrected reading - 76°

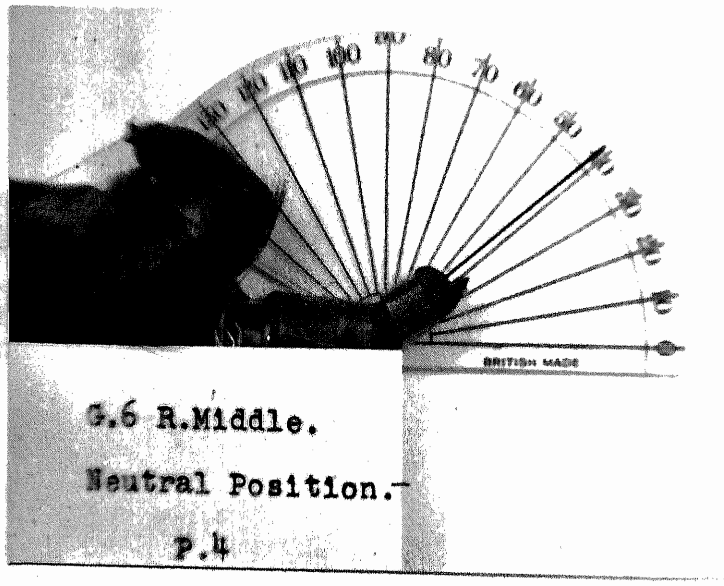


**Fig. 135** Photograph of the right middle finger of monkey G.6. in the Neutral Position before the operation.
Photographic reading - 42°
Corrected reading - 40°

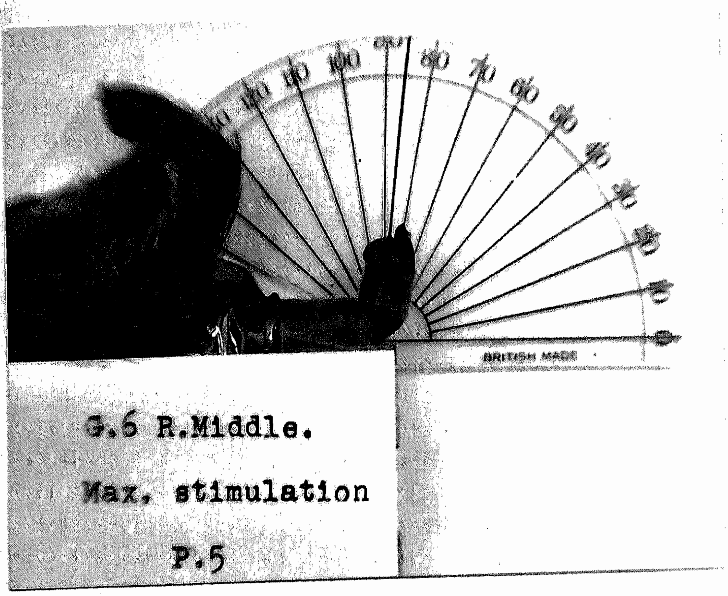


**Fig. 136** Photograph of the right middle finger of monkey G.6. in Maximal Flexion before the operation.
Photographic reading - 85°
<u>Corrected reading</u> - 78°

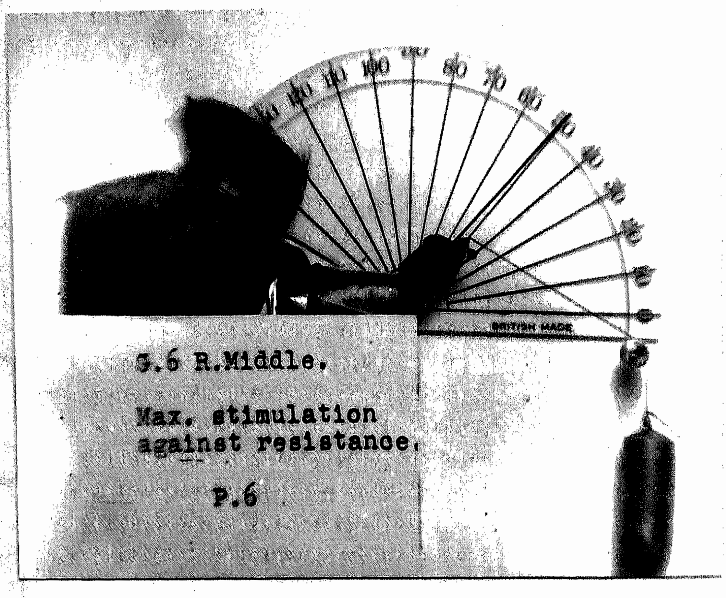


**Fig. 137** Photograph of the right middle finger of monkey G.6. in Maximal Flexion and against resistance before the operation.
Photographic reading - 50°
<u>Corrected reading</u> - 47°

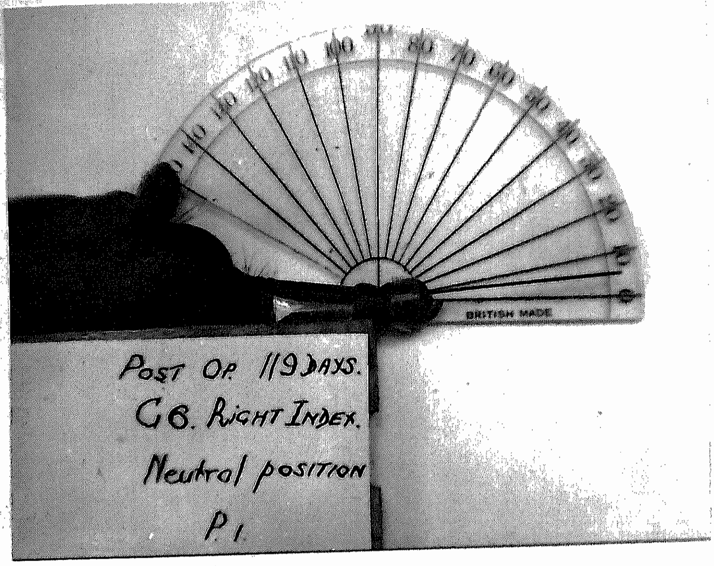


Fig. 138 Photograph of the right index finger (venous graft) of monkey G.6. in the Neutral Position 119 days post-operatively.

Photographic reading - 6°

Corrected reading - 6°

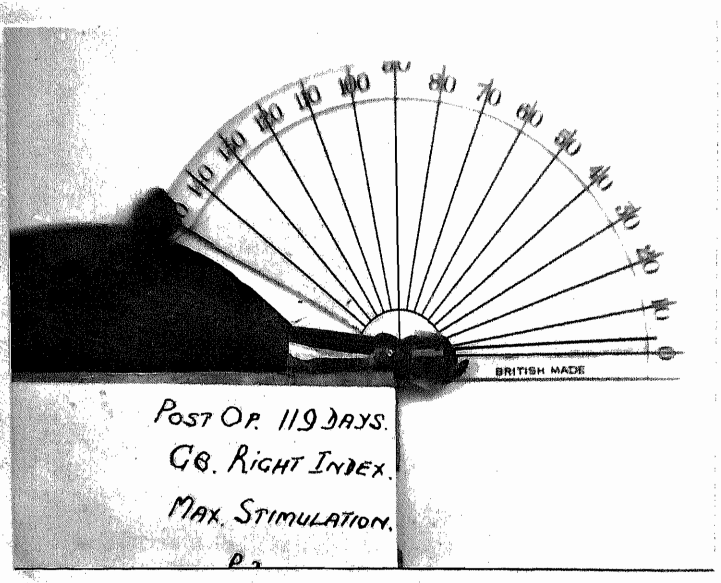


Fig. 139 Photograph of the right index finger (venous graft) of monkey G.6. in Maximal Flexion 119 days post-operatively.

Photographic reading - 4°

Corrected reading - 6°

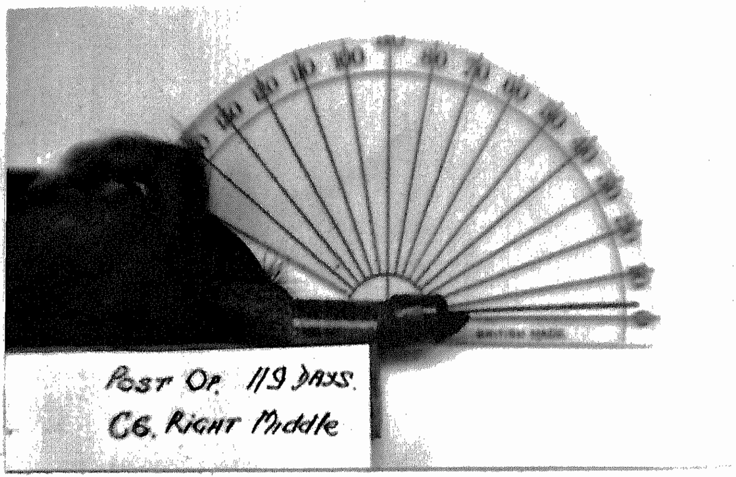


Fig. 140 Photograph of the middle finger (Control) of monkey G.6. in the Neutral Position 119 days post-operatively.

Photographic reading - 3°
Corrected reading - 6°

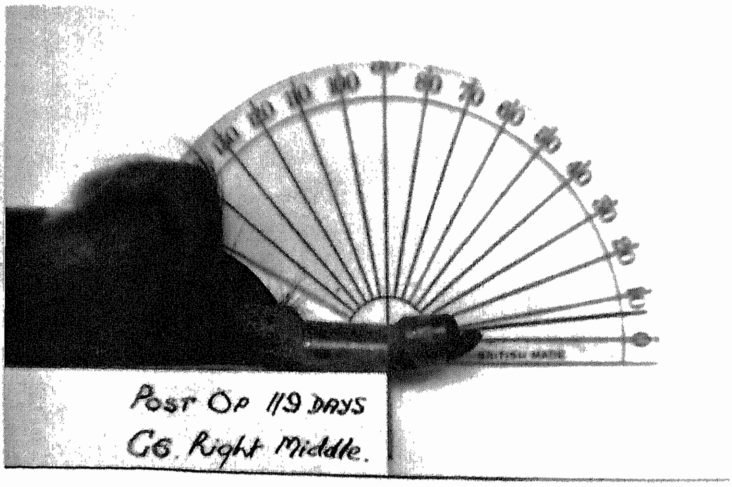


Fig. 141 Photograph of the middle finger (Control) of monkey G.6. in Maximal Flexion 119 days post-operatively.

Photographic reading - 6°
Corrected reading - 12°

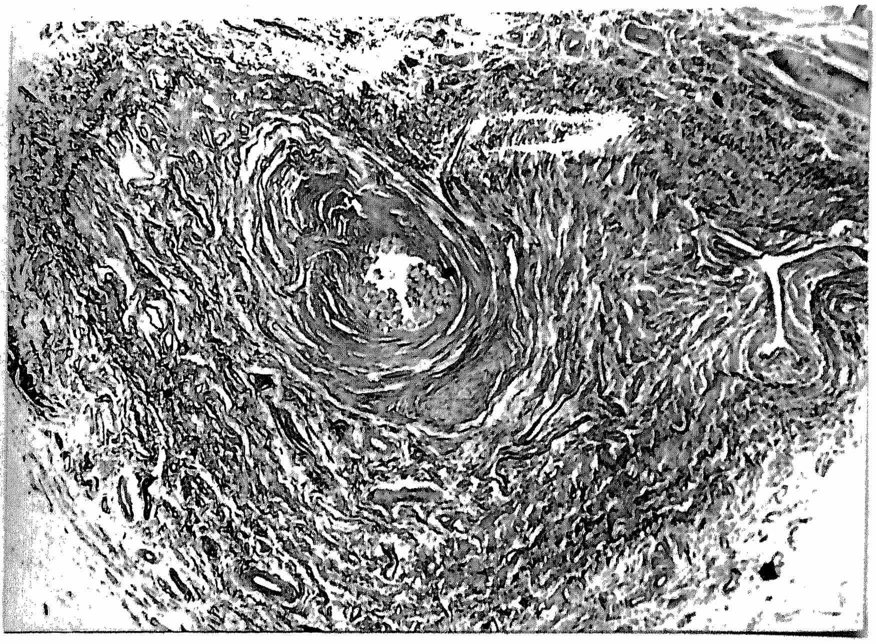


**Fig. 142** Photomicrograph of a transverse section of the flexor digitorum tendon and the venous graft in the region of the suture line in the index finger of monkey G.6.

Weigert X 70

Note the venous graft characterised by its elastic laminae. The tendon which has been almost completely replaced by fibro-vascular connective tissue is intimately adherent to the venous graft. Note the vascularity of the perivenous connective tissues and the suture material within the tendon.

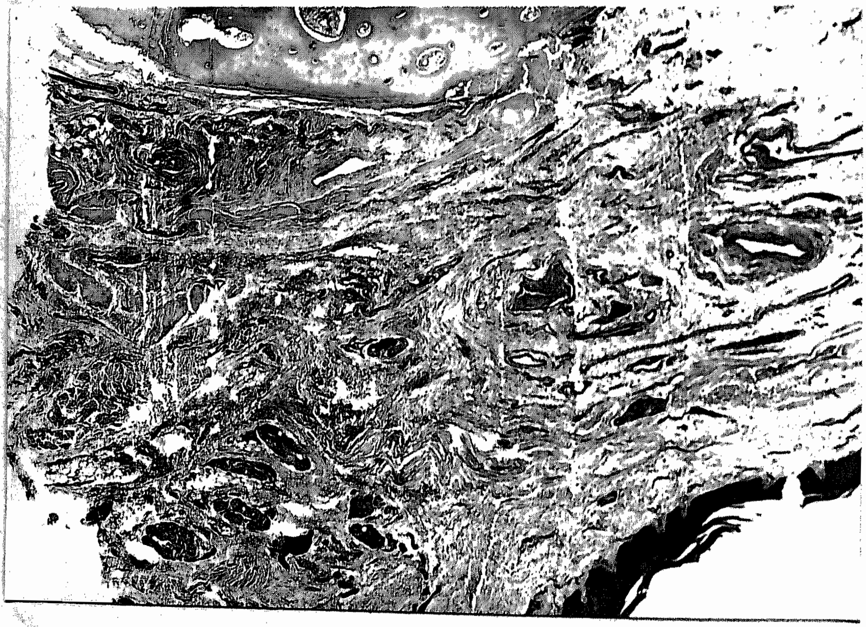


**Fig. 143** Photomicrograph of a transverse section of the tendon of monkey G.6. (Control) in the region of the suture line.

Haematoxylin and Eosin X 35

A few tendon bundles are evident and most of the tendon has been replaced by fibrous connective tissue. There is no evidence of a tendon sheath.

**Monkey No:** G.6.

**Date:** 12.1.51.

**Sex:** Male.

**Weight:** 11 lbs. 10 ozs.

**Anaesthetic:** Nembutal 2 ccs. injected into the left lesser saphenous vein.

**Pre-operative Recordings of Flexion:** (Table 16).

| DIGIT | NEUTRAL POSITION | MAXIMAL FLEXION | MAXIMAL FLEXION AGAINST RESISTANCE | RANGE OF FLEXION |
|---|---|---|---|---|
| RIGHT INDEX | 34° | 76° | 76° | 42° |
| RIGHT MIDDLE | 40° | 78° | 47° | 38° |

Table 16. The pre-operative recordings of flexion at the distal interphalangeal joints of the right index and middle fingers of monkey G.6. (Figs. 132 to 137). The range of flexion at the distal interphalangeal joints of the index and middle fingers is 42° and 38° respectively.

**The Operation:** The operative procedure was the same as that described in the text, the venous graft ensheathing the flexor digitorum profundus tendon of the index finger only. The middle finger acted as the CONTROL.

**Duration of Operation:** 2½ hours.

**Recovery from Anaesthesia:** About 3½ hours after induction.

**Post-operative Progress:**

| | |
|---|---|
| 13.1.51. | Animal subdued. |
| 14.1.51. | Animal extremely aggressive. Evidence of attempts at removal of the plaster. |
| 23.1.51. | The plaster cast was very tattered at the edges but intact at the wrist joint. |
| 1.2.51. | The animal had succeeded in removing the plaster cast from the hand but not from the forearm. |
| 25.3.51. | The affected fingers were held in the extended position. Active flexion at the interphalangeal joints was not observed. |

18.4.51. No evidence of active flexion at the interphalangeal joints. The period of immobilisation of hand was about 19 days.

Post-operative Recordings of Flexion: (Table 17).

Date: 9.5.51. - 119 days post-operatively.

Anaesthetic: Nembutal 1.5 ccs. injected into the right lesser saphenous vein.

Weight: 11 lbs. The animal had lost 10 ozs. in weight. Its general appearance was healthy.

Observations: The original skin incisions had healed well. The affected digits were extended, the pulps were atrophic, and the skin of the terminal phalanges shiny and depigmented. The interphalangeal joints of both digits had a poor range of passive flexion.

| DIGIT | NEUTRAL POSITION | MAXIMAL FLEXION | MAXIMAL FLEXION AGAINST RESISTANCE | RANGE OF FLEXION |
|---|---|---|---|---|
| RIGHT INDEX (Venous graft) | 6° | 6° | Not recorded | 0° |
| RIGHT MIDDLE (Control) | 6° | 12° | Not recorded | 6° |

Table 17. The post-operative recordings of flexion at the distal interphalangeal joints of the right index (venous graft) and middle fingers (CONTROL) of monkey G.6. (Figs. 138 to 141).
The range of flexion at the distal interphalangeal joints of the index and middle fingers was 0° and 6° respectively.

The Functional Results (Monkey G.6).

(a) The Venous graft (Index finger)

The pre-operative range of flexion of the distal interphalangeal joint of the index finger was 42°. 119 days after placing the venous graft around the sutured tendon, the range of flexion was 0°. Therefore the post-operative range of flexion was 0% of the normal.

(b) The Control (Middle finger)

The pre-operative range of flexion of the distal interphalangeal joint of the middle finger was 38°. 117 days after tendon suture without using a venous graft the range of flexion was 6°. Therefore, the post-operative range of flexion was 15.8% of the normal.

The Histological Findings (Monkey G.6).

Right Index Finger (Venous graft)

The longitudinal sections were not suitable for study as these sections were unfortunately not cut deep enough. In the transverse sections, in the region of the suture line, the tendon was found to be almost completely replaced by fibro-vascular tissue in which very few tendon fibres were visible. The venous graft, identifiable by its elastic laminae (Fig. 142) could be seen surrounding the site of suture, but no muscle fibres were observed. No sheath space was evident, the venous graft being firmly adherent to the tendon. Numerous foci of foreign body reaction were seen in the wall of the vein.

Right Middle Finger (Control)

Except at its insertion, where a normal sheath space was evident, the tendon was adherent to the surrounding connective tissues throughout its digital course. In the region of the suture line only a few tendon bundles were evident, most of the junction having been replaced by fibro-vascular connective tissue. (Fig. 143). Elsewhere the tendon displayed normal cytology.

| PRE-OPERATIVE RECORDINGS | | | | POST-OPERATIVE RECORDINGS | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| MONKEY | NEUTRAL POSITION | MAXIMAL FLEXION | RANGE OF FLEXION | MONKEY | NO. OF DAYS AFTER OPERATION | NEUTRAL POSITION | MAXIMAL FLEXION | RANGE OF FLEXION | PERCENTAGE OF NORMAL FLEXION |
| G.1. | 40° | 75° | 35° | G.1. | 267 | 10° | 11° | 1° | 2.9% |
| G.2. | 30° | 93° | 63° | G.2. | 265 | 22° | 70° | 48° | 76.2% |
| G.4. | 39° | 95° | 56° | G.4. | 85 | 4° | 18° | 14° | 25.0% |
| G.5. | 37° | 85° | 48° | G.5. | 117 | 6° | 12° | 6° | 12.5% |
| G.6. | 34° | 76° | 42° | G.6. | 119 | 6° | 6° | 0° | 0% |
| | | | | | | | | | Average 23.3% |

INDEX FINGER - VENOUS GRAFT

| PRE-OPERATIVE RECORDINGS | | | | POST-OPERATIVE RECORDINGS | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| MONKEY | NEUTRAL POSITION | MAXIMAL FLEXION | RANGE OF FLEXION | MONKEY | NO. OF DAYS AFTER OPERATION | NEUTRAL POSITION | MAXIMAL FLEXION | RANGE OF FLEXION | PERCENTAGE OF NORMAL FLEXION |
| G.1. | 38° | 75° | 37° | G.1. | 267 | 29° | 40° | 11° | 29.8% |
| G.2. | 35° | 60° | 25° | G.2. | 265 | 20° | 40° | 20° | 80.0% |
| G.4. | 46° | 70° | 24° | G.4. | 85 | 23° | 30° | 7° | 29.1% |
| G.5. | 33° | 58° | 25° | G.5. | 117 | 34° | 46° | 12° | 48.0% |
| G.6. | 40° | 78° | 38° | G.6. | 119 | 6° | 12° | 6° | 15.8% |
| | | | | | | | | | Average 40.5% |

MIDDLE FINGER - CONTROL

<u>Table 18</u>. Columns 4 and 9 indicate the pre-operative and post-operative recordings of the ranges of flexion at the distal interphalangeal joints of the right index (venous graft) and middle (control) fingers. The last column indicates the percentage of normal flexion after tendon suture. Note that the average post-operative percentage of normal flexion at the distal interphalangeal joints of the digits in which venous grafts surrounded the sites of tendon suture was <u>23.3%</u>, whereas, the post-operative percentage of normal flexion of the control digit was <u>40.5%.</u>

# CHAPTER 5

## ANALYSIS AND DISCUSSION OF THE RESULTS

It has already been pointed out, that for the purposes of assessing the functional results in this experiment, the range of active flexion at the distal interphalangeal joints was regarded as an index of tendon function. The proposed method of calculating the amount of work done, by determining the range of flexion against resistance, would have entailed the use of involved mathematical formulae, and the information derived would neither have been comparable, nor of practical significance, for the following reasons:

(1) The neutral position of the distal interphalangeal joints differed in each case and therefore the mechanical advantage of each joint was a continuous variable.

(2) In most cases, the post-operative range of movements was negligible.

### (a) The Functional Results

The functional results of the five controlled experiments given in Table 18 can be summarised as follows :-

Average percentage of normal flexion at the distal interphalangeal joints.

Venous graft : 23.3% ± 14% (mean error)
Control : 40.5% ± 12% (mean error)
Difference : Average control - Average venous graft
= 17% ± 18% (mean error)

The mean difference of 17% suggests that the average functional results of the control tendons are better than the functional results of the fingers in which the venous grafts had surrounded the tendons. In the light of the mean error of this difference, ± 18%, it is clear that statistically the difference is not significant. The figures given, however, would support the clinical impression that the results of the control tendons are better than the venous ensheathed tendons.

(b) The Histological Findings

The main object of this study was to determine whether venous grafts, when placed around sutured tendons could reproduce synovial sheaths and thus prevent adhesions. Histological examination of the digits revealed that in no instance had synovial sheaths been formed. On the contrary, the venous grafts that ensheathed the digital flexor tendons were intimately adherent to the tendons and peritendinous connective tissues and were infiltrated by fibrous tissue. In fact, without the demonstration of the elastic fibres with the special stains, it was impossible to recognise the venous grafts. It is interesting to compare the extent of adhesion formation which occurred with venous grafts surrounding the palmaris longus tendons, with that which occurred within the ensheathed tendon. Although synovial-like sheaths had not formed around the palmaris longus tendons, the adhesions that formed were flimsy and translucent, and good passive gliding was possible between the two structures. The dense adhesions that formed between the venous grafts and the digital flexor tendons can be attributed to the poor blood supply of tendons in sheath formation.

The muscle fibres in the venous grafts used in the controlled experiment were completely replaced by fibrous tissue, but muscle tissue was still evident in the venous grafts that surrounded the palmaris longus tendons, and in the human autologous venous transplants. The reason for this discrepancy is readily appreciated when considering that the venous grafts employed in the controlled experiments were implanted for much longer periods. The degeneration and replacement of the muscle fibres of the grafts was anticipated, and coincides with pathological changes occurring in muscle tissue elsewhere, where, when denervated denervated or subjected to disuse it undergoes similar changes.

The behaviour of the elastic tissues of the venous grafts is remarkable especially in view of the opinion expressed by Cohen (1952) who in a dissertation on peripheral aneurisms and arterio-venous fistulae, stated that "elastic tissue is apparently lifeless and without cell head, but nevertheless capable of responding to appropriate stimuli, and indeed depends on these for its existence. The requisite stimulus for this elastic tissue is the rhythmical stretch of systole, that is pulsation, and this is essential for the well being of the elastic tissue, as the nucleus is to the cell." The effective stimulus for the maintenance of elastic tissue in veins is probably the tension exerted by the hydrostatic pressure of the venous blood, although rhythmical variations in venous pressure do occur as the result of respiratory excursions. The venous grafts used in these experiments were not subjected to pulsation or pressure, yet the elastic tissues survived periods of time of up to 267 days in the monkey, and 52 days in man, and in parts, showed remarkable preservation of their structure. (Figs. 89, 100 and 129). It is possible however, that had the venous transplants been allowed to remain in situ for longer periods, the elastic tissues would have disappeared.

The reaction of the flexor digitorum profundus tendons to the presence of silk sutures was more marked than that which occurred in the palmaris longus tendons. Not infrequently the tissue reaction in the palmaris longus tendons was minimal and occasionally absent, (Fig 62) whereas in the digital tendons the tissue reaction was invariably marked. (Fig 62) This discrepancy too, can probably be accounted for by the relatively better blood supply of tendons in paratenon.

It seemed that the tendons surrounded by venous grafts united more by fibrous tissue than actual tendon cells, a sign indicative of poor healing. This impression was supported by

| NEUTRAL POSITION OF INDEX FINGER (VENOUS GRAFT) | | |
|---|---|---|
| MONKEY | BEFORE OPERATION | AFTER OPERATION |
| G.1. | 40° | 10° |
| G.2. | 30° | 22° |
| G.4. | 39° | 4° |
| G.5. | 37° | 6° |
| G.6. | 34° | 6° |
| AVERAGE NEUTRAL POSITION | 36° ± 1.7°(M.E.) | 10° ± 3.7°(M.E.) |

Table 19. The average neutral position of the distal interphalangeal joints of the digits in which venous grafts surrounded the tendon was 36° before operation and 10° after operation. The neutral position had thus decreased by 26° ± 4° (M.E., which is certainly significant statistically).

| NEUTRAL POSITION OF MIDDLE FINGER (CONTROL) | | |
|---|---|---|
| MONKEY | BEFORE OPERATION | AFTER OPERATION |
| G.1. | 38° | 29° |
| G.2. | 35° | 20° |
| G.4. | 46° | 23° |
| G.5. | 33° | 34° |
| G.6. | 40° | 6° |
| AVERAGE NEUTRAL POSITION | 38° ± 2.5°(M.E.) | 22° ± 4°(M.E.) |

Table 20. The average neutral position of the distal interphalangeal joints of the control digits was 38° before the operation and 22° after the operation. The neutral position has thus decreased by 16° ± 4.8°(M.E., which is statistically significant).

the fact that tendon retraction at the sites of suture was more marked in the venous ensheathed tendons than in the control tendons. In tendon healing, during the phase of exudation and fibrinous union, the holding power of the tendon stumps for the suture is weak, and some degree of separation or retraction of the tendon ends is inevitable. At this stage the extent of retraction will depend upon the tendon tension and the security of the union. Following completion of the reparative process, if the tendon union is poor and mainly dependent for its integrity on fibrous tissue, further retraction and lengthening may occur following the resumption of functional activity.

The following method was used to estimate the extent of tendon retraction. If the neutral position of the distal interphalangeal joint of a finger is 40°, and should the activating flexor tendon of that joint heal in a lengthened condition, the neutral position will decrease to less than 40°, the range of decrease depending upon the extent of tendon lengthening, and this fact was used to determine tendon retraction. Tables 19 and 20 show the neutral positions of the terminal interphalangeal joints of the digits of the venous ensheathed tendons and control tendons, before and after operation.

It will be noted that the average decrease in the angle of the neutral position of the distal interphalangeal joints activated by the venous ensheathed tendons is $26^\circ \pm 4^\circ$ (mean error) while that of the control tendons is $16^\circ \pm 4.8^\circ$ (mean error). The difference of average decrease (venous graft - control) = $10^\circ \pm 5.7^\circ$ (mean error), which though not highly significant statistically, suggests that the neutral position of the venous ensheathed tendons had decreased more than that of the control tendons, thus indicating that the former tendons had healed in a more lengthened state, as a result of greater separation of the tendon ends.

The poor results obtained in this experiment, both functional and histological can be ascribed to the following: An important consideration in the restoration of function to sutured tendons, is one of blood supply. The blood supply of tendons, especially tendons enclosed in synovial sheaths is extremely meagre, and healing is dependent to a large extent on the nutrition derived from the peritendinous connective tissues. Should the healing tendon be isolated from its peritendinous connective tissues by tubes or wrappings, organic or inorganic, healing is jeopardised and the likelihood of prompt and secure union is diminished. Gonzalez who experimented on the healing of tendons surrounded by polythene tubes in the digital sheath of the dog, showed convincingly that "the control tendons healed much earlier than the polythene tendons." However, if the polythene tendons were immobilised for prolonged periods, at least forty days, strong healing did occur. The disadvantages of prolonged immobilisation, namely stiffness of the interphalangeal joints, and the subsequent difficulty in their mobilisation, have already been stressed.

Furthermore, the surrounding of sutured tendons with tubes or wrappings requires an adequate exposure of the tendon. This necessitates a lengthy incision of the tendon sheath and destruction of the annular ligaments, for it is almost impossible to surround a sutured tendon with any other material and not to crowd it unduly within the narrow confines of the digital sheath. Not infrequently, especially if a tube is to be placed around the tendon, the mesotenon has to be sacrificed, a procedure which further diminishes the blood supply to the tendon.

The poor results achieved with the use of venous grafts in these experiments, are in keeping with the results obtained by others working along ~~similar lines.~~ [illegible] of foreign materials. Davies and Aries (1937) who experimented in dogs stated that "injured tendons in which the sheath was not destroyed healed with an excellent gliding mechanism after five weeks. The insertion of animal membranes around these tendons formed a gliding mechanism which was inferior to the control experiments in which the sheath was left intact." Koch (1944) stated that, "the nutrition of the tendon within the finger must come in part from the capillaries of the subcutaneous tissue which overlies it. Blocking of the ingrowth of blood vessels at the line of suture jeopardizes the sound healing of the sutured tendon which is the first essential to the restoration of function."

Edgerton (1951) in a personal communication, stated that "we have during the last few years, carried out a number of experiments on dogs, trying to construct a satisfactory tendon sheath and (we have used material such as polythene film, fascia lata and paratenon. In general, we have found that) if anything ~~is~~ was placed around the tendon suture for a distance of more than 2 cm. that it prevents ed healing by blocking out the blood supply from the suture line. It has become very apparent to us that tendon anastomoses heal primarily with the aid of blood supply from the neighbouring soft tissues. If the reconstructed tendon sheath is much shorter than 2 cm. the problem of adhesions at either end still remains." Bunnell (1951), in a personal communication stated that "venous grafts have been used frequently for tendon and nerve junctures as far back as I can remember. They were not successful nor would one expect them to be from a physiological stand point." Mayer (1951) in a personal communication stated, that "it was in 1912 that I performed a similar series of experiments on the tendons of dogs and rabbits. I soon found that the implantation of a vein is an unphysiological procedure and tends to produce adhesions rather than prevent them. This fact in the light of my further studies, seems to me to be quite obvious since a vein is not adapted to gliding motion. It is inconceivable that the tendon will glide inside the vein since adhesions are bound to occur rapidly between the two structures. I would therefore strongly urge you to give up this particular method of attempting to prevent adhesions since it just doesn't work."

A consideration of the above facts clearly indicates that the surrounding of sutured tendons with tubes or wrappings is an unphysiological method of restoring tendon function.

# CHAPTER 6

## SUMMARY AND RECOMMENDATIONS

### SUMMARY

1. An attempt to reproduce tendon sheaths using autologous venous grafts has been undertaken in Cercopithecus aethiops (Blue Vervet Monkey). Ten venous grafts were tested. Five were placed around sutured tendons in paratenon, and the remainder around tendons in sheath formation. In no instance did synovial-like sheaths form. In the latter series, the experiment was controlled, and the results obtained expressed in terms of function. The functional results of the venous ensheathed tendons were worse than those of the controlled tendons.

2. The controlled experiment was confined to the digital sheath, an area notoriously liable to adhesion formation, and one which offered the most critical test of operative technique.

3. A method for the evaluation of function, following the repair of divided tendons in the experimental animal has been presented. Voluntary movement of joints in the experimental animal was obviously impossible, but the method employed in this experiment, namely, the electrical stimulation of muscles, and the photographic recording of the range of joint movement, presented no disadvantages.

4. The experimental animal used in this study was ideal, in that anatomical studies of the hand of this species, revealed features both structurally and functionally comparable to those in man.

5. The anatomical and physiological aspects of tendon action, the mechanics of tendon gliding, and the healing processes in divided tendons have been studied.

6. The fate of human autologous venous grafts has been investigated.

7. A review of previous methods employed to prevent peritendinous adhesions has been presented.

RECOMMENDATIONS

1. As has been pointed out, most of the experimental tendon work in animals was performed on tendons in paratenon and not in sheath formation, and furthermore in animals whose limbs subserved locomotion only and not prehension. Restoration of function to tendons severed in paratenon, on account of their relatively good blood supply and simple gliding mechanism, does not present the same problem as that which occurs with tendons divided in sheaths. If a contribution to the advancement of digital tendon surgery in man is to be made, then experimental work should be performed on tendons which are structurally and functionally comparable.

2. In the evaluation of the results of experimental tendon suture, passive movement of a tendon within its sheath is not necessarily synonymous with good tendon function. The gliding mechanism of a digital tendon may be anatomically intact, but if the subcutaneous tissues are indurated, the interphalangeal joints ankylosed, or the activating muscle degenerate, then the tendon is functionally useless. Tendon function, should therefore, be assessed in terms of active digital movement.

3. A detailed knowledge of the gross anatomy of tendons does not necessarily qualify one to perform tendon surgery. A consideration of the highly complex digital flexor mechanism, and the poor restoration of function which follows injury to this mechanism, clearly indicates that the treatment of this type of injury is a major surgical procedure and should not be undertaken by the occasional operator.

4. Although the use of tendon grafts has produced gratifying results, there is still much scope for the experimentalist in the field of tendon injuries. Since the advent of A.C.T.H. and cortisone, potent hormones having the ability to retard or reduce fibrous tissue formation, a new approach to this baffling problem may be evolved.

# CHAPTER 7

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# APPENDIX

Correspondence in connection with statistics relevant to hand and tendon injuries, was addressed to the following:

## Appendix A.

Office of the Workmen's Compensation Commissioner, Pretoria. (1951)

The Federated Employer's Mutual Assurance Company Limited, Johannesburg. (1951)

Transvaal Chamber of Mines, Johannesburg. (1951)

The Ocean Accident and Guarantee Corporation Limited, Johannesburg. (1951)

## Appendix B.

Royal Insurance Company Limited, Liverpool. (1951)

The Liverpool and London and Globe Insurance Company Limited, Liverpool. (1951)

The Employer's Liability Assurance Corporation Limited. London. (1951)

Norwich Union Fire Insurance Society Limited, Norwich. (1951)

Commercial Union Assurance Company Limited, London. (1951)

London Executive Council (National Health Service) London. (1951)

## Appendix C.

Metropolitan Life Insurance Company, New York. (1951)

Association of Casualty and Surety Companies, New York. (1951)

United States Department of Labour. (1951)

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