An Experimental Study of Healing of the Partially Severed Flexor Tendon in Chickens

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There is a lack of clinical and experimental studies of the treatment of incompletely transected tendons. The controversy concerning the source of flexor tendon nutrients is of important clinical concern in healing of the injured tendon; thus, the flexor tendon blood supply has cited as a reason for using specific tendon suture techniques, and as a rationale for preserving the superficialis tendon and its vincula during tendon repair surgery. Our knowledge of the normal physiology of digital flexor tendons and the mechanism of their healing process is deficient. The aim of this study was to investigate the relative importance of the synovial fluid and the blood supply respectively for the healing of partially severed flexor tendons. We observed the sequential histological and vascular changes which occur in healing of the partial lacerations in the dorsal and plantar aspects of the tendons. We observed the vascularities of the two partially severed tendon groups after injection of microfil and India ink through the femoral artery. In the healing process there was no sequential histological difference between the dorsal and the plantar severed tendons. The vascularity patterns of the healing tendons were significantly increased and the hypervascularity of dorsal severed tendons was greater than that of plantar severed tendons. Partially severed tendons were completely healed without surgical repair with dense collagen fibers without adhesion in most cases. We concluded from this study that the blood vessels appeared to play a significant role in the healing of the severed flexor tendons. An intact synovial environment did not seem to be required for healing of the severed tendon. It is not necessary to surgically repair the partially severed tendon for prevention of rupture and adhesion.

Key Words: Plantar and dorsal severed tendon healing, histological and vascular changes.

Controversy exists concerning the source of nourishment of the flexor tendons within the flexor sheath. Several workers studied the vascular anatomy of the flexor tendons, but not all authors are in agreement. To achieve functional tendon healing in the ensheathed portions of flexor tendons has been a difficult problem for surgeons. The tendon is relatively avascular, being made up largely of collagen fibrils with relatively fewer cells.

Mayer (1916) described the importance of the microcirculation of tendons in tendon transplantation. There are three sources of nourishment for tendons: (1) from the muscular branches; (2) from the vessels running in the surrounding connective tissue paratenon, mesotenon, and vincula; and (3) from the vessels of the bone and periosteum near the point of insertion of the tendon. The vascularity systems, the vincula longa and breva of both the profundus and sublumis tendons, are on the dorsal surface of the tendons and are supplied by the transverse communicating branches of the common digital artery. The digital tendon sheath is a unique, closed, mesenteric system, providing a synovial lining for its visceral and parietal surfaces. Tendon surgery within the digital sheath reflects the entire history of modern day hand surgery, as well as the evolving understanding of the physiology of tendon healing. However, some investigators suggested that digital flexor tendons may derive their nutrients primarily through diffusion from the synovium. Lundborg and Rank (1977) demonstrated the ability of flexor tendons to survive as well as to heal when lying free in the knee joint. Although the existence of a blood supply to the flexor tendons within the sheath is certain, its relative importance in the nutritional supply and healing process of these ten-
dons has not been settled. Suturing of the partial lacerations of the tendon in chickens decreases both the resulting tensile strength and gliding.

Kleintert (1973) stressed that the partial lacerations of the flexor tendons in chickens heal strongest and glide best if they are not sutured and not immobilized. This study was undertaken to reinvestigate the relative importance of the synovium of the tendon sheath and the blood supply for tendon healing.

MATERIALS AND METHODS

A total of 72 mature chickens, weighing 1.5 kilograms or more, were anesthetized with Nembutal (pentobarbital). The third toe of the adult chicken was incised through a midlateral incision after a tourniquet was applied. The flexor tendons were exposed, and a partial laceration (one-third of flexor tendon thickness) was made in the profundus tendon on the plantar aspect in 36 chickens and on the dorsal aspect in 36 chickens.

In order to determine whether the nutrients to the tendons within the digital flexor sheath come primarily from vascular perfusion or from synovial diffusion, we excised the synovium in one subgroup (36 chickens) and detached it from vascular attachments in another subgroup (36 chickens). No tendon repair surgery was done.

The skin and fascia were sutured immediately. The animals were returned to the cage without immobilization. The animals received an intramuscular injection of Kanamycin every 7 days to prevent infection. The animals were killed at three days, one week, 2 weeks, 4 weeks and 6 weeks after operation. Immediately after death, each animal’s 3rd toe was opened. There were no distinct sequential gross differences between the dorsal and plantar severed groups. We found no evidence of hypertrophic scar formation at injured sites. It was necessary to remove the tendon together with surrounding soft tissue and periosteum. At least three slices were obtained from each specimen. The slices were fixed overnight in formalin, embedded in paraffin and sectioned with a microtome. Some of these sections were stained with hematoxylin-eosin and Masson-trichrome.

For the microangiography, ten of the chickens were anesthetized lightly with Nembutal. The femoral artery and vein were identified in the inguinal area. After insertion of an angio-catheter into the femoral artery, the proximal ligation of the femoral artery and section of the femoral vein were done and perfused with heparinized solution until a clear solution was returned from the cut femoral vein. Thereafter, the angiogram dye (India ink solution or yellow microfil solution) was injected through the catheter by manual pressure, the animals were sacrificed. The specimen was obtained and it was dehydrated in 70%, 80%, 90%, 95%, and 100% alcohol and was made transparent by tricresyl phosphate-tributyl phosphate solution and observed under the light microscope.

RESULTS

Normal tendon

Tendons are classified as dense, regularly arranged, connective tissue. This tissue is composed of tenocytes, collagen and ground substance. Tendon cells are the predominant cell type and are arranged in long parallel rows in the spaces between the parallel collagen bundles. Tendons are enclosed by a tendon sheath (Fig. 1). Histologically, the membranous part of the flexor tendon sheath exhibits the characteristics of a synovial membrane; a loose fibrovascular tissue, covered by a layer of polyhedral, synovial-like cells.

Tendons receive their blood supply from vessels in the perimysium, their peristeal attachment, and the surrounding tissue via vessels in the paratenon, mesotenon, or vincula.

The interior of the tendons remains well supplied by a longitudinally oriented intrinsic vascular system with a rich anastomosis with transverse branches (Fig. 2). The dorsal part of the profundus tendon contains a well developed vascular network and vascular loops penetrate vertically into the tendon substance. The plantar 1/4 to 1/3 of the profundus tendon is devoid of blood vessels (Fig. 3).

Plantar severed tendon group

In no case was there any adhesion formation between the injured tendon and perisheath tissue. After three days, the gap of the severed tendon was rounded off and infiltration of inflammatory cells and blood elements was noted (Fig. 4).

At the injured site, from the first week there were scattered zones of cell proliferation with early deposition of collagen fibers and bridging of the gap. There was proliferation of the surrounding connective tissue cells and exudation of blood elements so that the healing tendon was surrounded by a friable, highly cellular granulation tissue composed of fibroblasts, capillaries and formed blood elements which not only surrounded the tendon but also entered the closely apposed wound space between the severed stumps (Fig. 5).
**Fig. 1.** Normal tendon tissue, which is composed of tenocytes, collagen and ground substance, is covered with a visceral synovial sheath (H & E, ×200).

**Fig. 2.** Intrinsic vascular system of the normal tendon. Many longitudinal systems of capillaries are noted (India ink injection, ×20).
At 10 days, new collagen fibers appeared in the granulation tissue between the injured sites; these fibers were perpendicular to the long axis of the tendon and were obviously the product of the fibroblasts growing between the stumps from the investing connective tissues (Fig. 6).

At three weeks it was almost impossible to distinguish the injured sites, because the cut-gap was completely filled with bridging collagen fibers (Fig. 7).

The healing processes were not remarkably different between the cases of lacerations in which the tendon sheath was excised or kept intact. The excision of the sheath did not delay tendon healing. With the healing of the perisheath tissues, the synovial-like layer was rapidly reconstituted and a new gliding pathway was formed. The hypervascularity of the partially severed tendons was common to all healing tendons (Fig. 8). Mobilization of the plantar partially severed tendons markedly diminishes adhesion formation around the injured sites. The healing had progressed in its maturity with a decrease in its cellularity and vascularity.

**Dorsal severed tendon group**

In the histological healing process, in neither of the
Fig. 5. Longitudinal section of the plantar severed site at seven days. There is extensive proliferation of the granulation tissue arising in the surrounding tissue (H & E, ×100).

Fig. 6. Cross section of the plantar transected tendon at 10 days after operation. Some new collagen fibers are noted in the granulation tissue between the injured sites (Masson-trichrome, ×200).
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Fig. 7. Longitudinal section of plantar severed sites healed well three weeks after laceration. It shows collagen in the wound oriented in the long axis of the tendon. The cut-gap is completely filled with bridging collagen (H & E, x200).

Fig. 8. The microangiogram of the plantar severed tendon at two weeks. There was hypervascularity at the injured site of the plantar side (Microfil injection, x10).

two groups was there any difference between those who had the synovial excision and those who had the vinculum cut. Histologically, epitenon proliferation was marked and collagen remodelling across the injured site was well advanced at 28 days (Fig. 9).

Damage to the vicular blood supply of the flexor tendon increased the adhesion formation. In 3 cases (8%) adhesions were cellular and well developed at 14 days and densely engulfed the injured site for 5 to 10 mm in each direction at 28 days (Fig. 10).

Severed vincula quickly became reattached to the bed and revascularized. Our experiments with dorsal tendon healing showed that production of the granulation tissue following injury was more massive than on its plantar side. This could be the consequence of a richer blood supply to the injured tendon sheath and vicular system on the dorsal side. Microscopic findings of the damaged flexor tendons usually showed obliteration of the normal dorsal longitudinal channel with an increase of vascularity within the tendon and a disorganization of the normal tendon fascicle (Fig. 11).

**DISCUSSION**

The repair of flexor tendons which have been divid-
Fig. 9. Longitudinal section of the dorsal severed tendon at 28 days after operation showing epitenon proliferation and collagen remodelling across the gap (Masson-trichrome, ×200).

Fig. 10. Cross section of dorsal injured tendon after 14 days. The adhesion area shows the hypercellularity, hypervascularity and fibrosis around the tendon tissue (Masson-trichrome, ×100).
ed within the digital sheath remains an unsolved problem in surgery of the hand. The importance of the nutrition of a tissue with respect to the way it heals has been appreciated and study of the blood supply to tendons has been an important facet of research. There is some controversy regarding the importance of blood flow through intrasynovial tendons. Potenza (1962) stressed the importance of the tendon blood supply in a detailed anatomical study of the vasculature of the flexor. It is now understood that the blood supply of the tendon does not originate from its bony insertion or muscle origin, nor from the paratenon (Young and Weeks 1971; Caplan et al. 1975).

Microdissections have shown that there is a mesotenon on the tendon which brings to it a vascular network in an arcade comparable to the mesentery of the gut. In the digit the mesotenon is more important. This blood supply provides nutrition for the tendon to segments that do not exceed 2 or 3 cm (Edward 1946; Brockis 1953; Smith 1962).

Peacock (1959) apportioned the relative contribution of the intratendinous longitudinal and segmental vascular system. This vincular system exists on the dorsal surface of the tendons and originates from the transverse communicating branches of the volar digital artery. Since most of the intratendinous vessels in the digital sheath are in the dorsal portion of the tendons, some authors recommend placing sutures in the volar half of the tendons during surgical repair so as not to disturb these vessels. It is generally realized that preservation of as much as possible of this segmental vascular supply is essential for preservation of the blood supply in the tendon (Verdan 1960; Weeks 1965). In our study, the dorsal severed tendons with damage of the vascular system had marked hypervascularty through the entire depth of the damaged portion. It may be proliferation or reattachment of blood vessels from the vincular system of the dorsal side.

During recent years, evidence has been presented indicating that nutrition via diffusional pathways from the synovial fluid might also be of significance for flexor tendons normally.

The role of the synovial fluid as a nutritional medium is a question of great importance for any hand surgeon as he must know how to handle the structure producing the fluid—the synovial tendon sheath. The digital tendon sheath is a unique, closed, mesenteric system, providing a synovial lining for its visceral and parietal surface. It has a threefold function: (1) it allows for smooth gliding of its contained

**Fig. 11.** Note the pronounced vascularity of the dorsal side scar in contrast to the plantar tendon portion at two weeks after operation (Microfil injection, ×10)
tendinous structures in flexion and extension, (2) the specialized reinforcing collagen banding or pulley system provides a fulcrum to aid in mechanical advantage for the motion of flexion, and (3) it serves a nutritive function in providing a contained bursal environment for synovial fluid (Landi et al. 1980).

Recently there has been increasing support for the concept that synovial diffusion is the major nutrient pathway to the flexor tendons in Zone II, and restoration of the tendon's synovial fluid environment has been advocated to maintain this nutrient pathway. Closure of the digital sheath is now being performed with increasing frequency after tendon repair (Eiken et al. 1975).

In our study, we examined the flexor sheath integrity in the severed chicken flexor tendons; varying degrees of sheath integrity (sheath excised or incised and repaired) did not affect the healing pattern of partially severed tendons. Therefore, closure of the sheath to maintain the synovial environment of the tendon may not be necessary for the healing tendon’s nutrition. However, Katsumi and Tajima (1981) have demonstrated that the extracellular tissue fluid, like synovial fluid, is capable of providing necessary nutrients to tendons. Our results support this concept that the extracellular tissue fluid is capable of providing nutrients to the flexor tendons in Zone II. The diffusion of nutrients from the surrounding tissue remains capable of repairing the plantar partially severed tendons during the healing phase.

Traditionally, lacerations of the flexor tendon within the digital sheath have been thought to heal by extrinsic adhesions from peripheral fibroblasts. In contrast, the intrinsic healing capacity of the flexor tendon has been suggested by the observation of “rounding off” or “capping” of lacerated human flexor tendons at surgery in the absence of peripheral adhesions. Although sheath closure does not seem to have a role in the nutrition of tendons, it is possible that sheath closure may affect tendon gliding by altering the nature of the adhesions that form after tendon injury (Birdsell et al. 1966; Matthews and Richards 1974). There is no clinical or experimental study on the treatment of incompletely transected tendons. The suturing of partial tendon lacerations has been recommended by Kleinert (1973). However, in our study suturing such partial lacerations in chickens decreased both the resulting tensile strength and gliding. It is apparent that tendon suturing is not only unnecessary but also interferes with the normal biological process of tendon healing.

Immobilizing a partial tendon laceration in a chicken also causes a decrease in the tensile strength and in gliding. There are three potential problems that could result from not suturing a partial tendon laceration; namely, complete tendon rupture, decrease of tendon gliding, and development of trigger finger. The rupture rate of partial tendon lacerations in chickens is significantly higher in sutured tendons than in unsutured tendons. In our study, only two cases of spontaneous ruptures occurred in the plantar severed tendons, and the best result was noted in the cases which were not sutured and not immobilized.

At present, it is impossible to accurately define the upper limit of a partial tendon laceration which need not be sutured. We studied the partial laceration up to 75 percent of its cross-sectional diameter. The cause of spontaneous rupture is usually unknown, but the mechanical stress concentration may be a major factor. We observed that tendon gliding in these chickens would be satisfactory because any adhesions are less dense in tendons if they are not sutured and not immobilized after creation of a partial laceration up to 75 percent of its diameter. From this study, we thought that partial lacerations of flexor tendons in chickens heal well and glide best if they are not sutured and not immobilized.

The chicken was first chosen by Lindsay and Thompson (1960) as a model for flexor tendon studies, because all the important structures of the human fingers are present in the chicken toe. Furthermore, toe length makes the chicken a convenient model for experimental tendon study. However, the applicability of the chicken model to the human is always a questionable subject (Farkas et al. 1974; Greenlee et al. 1975). Additional studies to examine the effect of sheath integrity and alteration of the blood supply of the flexor tendon following injury should be carried out in the monkey flexor system.

Conclusion

Partially severed tendons on different sides were used to investigate the role of synovial diffusion versus vascular perfusion in the nutrition of chicken toe flexor tendons. A synovial fluid environment is not necessary for the repair of a damaged tendon. Partially severed tendons healed well without surgical suture and glided best except in some cases. Vascular perfusion plays an important role in the healing phase of severed tendons.

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