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INTRAVITAL OBSERVATION ON THE MICROVASCULAR ANATOMY AND MICROCIRCULATION OF THE TENDON

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THE ARCHITECTURE OF THE TENDON

The tendon is a connective tissue structure composed of closely packed collagen fibers and protein-mucopolysaccharide. The collagen fibers are as long as the tendon (Bucher 1962) and where they do anastomose with each other they do so at acute angles. The cell responsible for the elaboration of the collagen and the protein-mucopolysaccharide and maintenance of the integrity of the tendon is the "Tenocyte" or fibroblast (Hall M. C. 1965). The collagen fibres are grouped together in primary bundles (Schneider 1959) which in turn are assembled into larger "secondary bundles" (Schneider 1959) or fascicles (Edwards 1946). The secondary bundles then form tertiary bundles (Schneider 1959) which together comprise the tendon. Tendons vary in length and in cross-sectional area and the latter varies with the part of the tendon, diminishing in a proximodistal direction. Edwards (1946) claims that if the secondary bundles or fascicles are considered as the "unit structure" of tendon, then some uniformity exists. These fascicles are hexagonal in shape with a cross sectional area between 0.125–0.375 square millimeters.

The tendon bundles are surrounded by a woven mesh of loose connective tissue, the peritenoneum internum or endotenon. This tissue holds the bundles together, permits some movement of bundles with relationship to each other and carries all the blood vessels, lymphatics and nerves. It has elastic fibres (Hirai 1959) which tend to draw the tendon bundles into a wavy formation when relaxed. At the musculotendinous junction there is an intimate relationship between the sarcomeres and the collagenous fibril bundles, although no direct continuity exists (Boyd 1960). Electron microscopic studies have shown that the sarcolemma is intact at the junction, and that the tendon bundles are invaginated into the ends of muscle fibers in the many terminal indentations of the outer sarcolemmal layer. In this way, a considerable surface contact between the muscle fiber and the collagenous fibrils is achieved. Each group of muscle fibers enclosed in perimysium continues as a secondary bundle or fascicle and the peri-

mysium is continuous with the endotenon (Edwards 1946). This very regular arrangement does not hold true where muscle fibers join the tendon obliquely, but the general organization pattern is similar.

At the tendo-osseous junction the collagen fibers continue as the perforating fibers of Sharpey. The endotenon becomes continuous with the periosteum, but the cortical zone of the bone at the insertion of the tendon, as long as the cross sectional area of insertion is not large, is free of periosteum (Schneider 1959).

The whole tendon is surrounded by a fine connective tissue sheath, the peritenoneum externum or epitenon, which is continuous throughout on its inner surface with the endotenon.

Surrounding the tendon is a loose, fatty, areolar tissue, the paratenon (Smith 1965). Its mechanical function is to allow the tendon to glide freely against the surrounding tissue (Brand 1961, Stanisavljevic 1962). In areas where a tendon passes over a structure which might harm it, that is, zones of local pressure and friction, the paratenon is replaced by a synovial sheath or bursa and in the tendon in corresponding areas either cartilagenous plates or sesamoid bones may develop. The visceral layer of this tenosynovium is dense, fibro-elastic, and closely adheres to the epitenon (Edwards 1946). The visceral and parietal layers of the tenosynovium are continuous with each other at the ends of the tendon synovial sheath as well as through mesentery like structures, the mesotendons, which in some areas have been designated as vincula tendinum.

THE BLOOD SUPPLY TO THE TENDON

The tendon is a well vascularized tissue. The blood supply is less profuse than that of muscle but there is no tendon without a blood supply. (Biesalski and Mayer 1916, Smith 1965)

A tendon receives its blood supply at the musculotendinous junction, along its length, whether it be in paratenon or tendon sheath, and in the region of its insertion.

A. The Musculotendinous Junction

There are a number of longitudinal vessels, both arterial and venous, which traverse the musculotendinous junction (Wollenberg 1905, Arai 1907, Ray 1914, Dychno 1936, Edwards 1946). Most of these vessels run in the depth of the tissues. The observation of Rau (1914)

that vessels which in youth cross the musculo tendinous junction in the depth, later in life assume a superficial position, has not been substantiated by subsequent investigators. Both Rau (1914) and Dychno (1936) made the observation that frequently one or two of these vessels appear as chief vessels and after crossing the musculotendinous junction traverse the full length of the tendon, only to loop back on themselves at the musculo-osseous junction.

Edwards (1946) pointed out that only the vessels in perimysium continue into the tendon, but that the capillary circulation of the muscle and of the tendon is completely separate and distinct. The capillaries adjacent to the sarcomeres loop back at the musculotendinous junction to drain into the venules of the muscle and no capillary anastomoses exist at the junction of the two tissues.

In addition to this longitudinal system, one frequently encounters smaller arteries and veins which divide near the musculotendinous junction, with one branch joining the muscle and the other the tendon.

B. The Paratenon

The paratenon contains many vessels which are largely responsible for the blood supply to the tendon (Wollenberg 1905, Arai 1907, Rau 1914, Dychno 1936, Edwards 1946, Smith 1965). At frequent intervals, small vessels arise from neighbouring vessels and run transversely through the paratenon towards the tendon. On approaching the tendon, these vessels may branch several times before assuming a direction parallel with the longitudinal axis of the tendon. It is at this point that they join the tendon circulation (Edwards 1946, Smith 1965).

C. The Synovial Tendon Sheath

The synovial tendon sheaths have rich vascular nets on their surface as well as in their depths (Dychno 1936, Edwards 1946). These are more profuse in the areas of the pulleys (Smith 1965). The visceral layer of the tenosynovium receives a rich blood supply through the mesotendons as well as through its connections with the parietal layer at the ends of the synovial tendon sheaths (Edwards 1946). The mesotendons are nothing more than prolongations of the paratenon (Dychno 1936), although in this instance, the paratenon is interposed between two layers of synovial tissue. As in the paratenon, the number of vessels in a particular region varies. The "circulation" in the visceral layer of the tenosynovium (Edwards 1946, Observations made on the cow)

consists of a superficial capillary network and a much deeper plexus of arteries and veins. The capillaries loop to the surface from the underlying arterioles and venules. It is only the deep plexus which communicates with the tendon "circulation" by short anastomotic channels.

D. The Tendon Bone Junction

Wollenberg (1905), Arai (1907), Rau (1914), Dychno (1936) and Nichols (1954) were unable to demonstrate any direct communication between the tendon circulation and bone. They all describe anastomoses between the tendon vessels and periosteum. Only Edwards (1946) claims to have been able to demonstrate in some areas branches passing directly through to the cortical layers of bone, but he also points out that these vessels are small, few and irregularly distributed.

The vessels in the tendon at its insertion anastomose with those present in the periosteum and only by means of this indirect communication have a connection with the osseous circulation.

The arrangement of the internal vascular architecture of the tendon is primarily one of longitudinally oriented blood vessels which run in the endotenon in the long axis of the tendon (Arai 1907, Biesalski and Mayer 1916, Dychno 1936, Edwards 1946, Braithwaite and Brockies 1951, Brockis 1953, Smith 1965).

According to Edwards (1946) these vessels are arteriolar in size with a well developed tunica media and are arranged around the fascicles. Accompanying each arterial channel are two veins, one on each side, which communicate frequently with each other, usually in the neighbourhood of a tributary or a branch (Edwards 1946, Brockis 1953). Dychno (1936), on the other hand, found only occasionally larger vessels. Most of the vessels he was able to demonstrate histologically were capillaries with a single endothelial lining.

The capillaries arise from the arteriolar branches, form loops which then drain into several venules. These loops may run from one longitudinal channel to another or back to the parent vessel. The capillaries are intra fascicular and do not penetrate the collagen bundles (Dychno 1936, Edwards 1946).

This "internal" vascular system is fed from the vessels present in the epitenon. Branches arise from the epitenon vessels and enter the tendon substance radially along the endotenon. These either anastomose directly with the longitudinal vessels, or divide first into ascending and descending branches before doing so.

The architecture of the epitenon vessels is very variable. It is generally very profuse in areas where the tendon is in paratenon, but varies not only from tendon to tendon but also in different areas of the same tendon. Certain areas of the epitenon have a highly characteristic and organized vascular architecture (Guse 1963, Winter 1965). No epitenon vessels are located on the side of the tendon which comes in contact with pulleys or where friction would be at its maximum (Smith 1965). An excellent example of this is the arrangement of the vincula tendinum on the dorsum, the nonfriction area of the tendons within a tendon sheath.

THE METABOLISM OF THE TENDON

A co-relationship exists between the blood supply of a tissue and its metabolic requirements. The information on tendon metabolism, however, is very scanty. Neuberger (1953) measured a small but definite turnover of amino acids in the collagen of adult tendons and Peacock (1959) found the respiratory activity to be 0.1 microliters per unit weight per hour.

White (1964) has estimated the average rate of blood flow in tendon to be 0.10 cubic centimeters per gram per minute. The contentions of Berkenbusch (1887) and Rau (1914) that the blood supply in tendon varies with age, have found some confirmation in the experiments of Rothman (1965) who found, that there is an apparent decrease in the capillary bed of a tendon with aging. More recently Rothman (1967) has also demonstrated that a significant decrease occurred in the capillary bed volume in tendon tissue following a six week period of immobilization.

THE INVESTIGATION

No intravital study of the microvascular anatomy and microcirculation of the tendon could be found in the literature.

All studies published to date have been carried out on dead specimens. The vessels of the tendons prior to study were usually filled with a contrast medium. The tendon was then in accordance with the technique employed suitably processed and examined microscopically or by angiography. Such an approach has certain obvious inherent draw-

backs. The accuracy of the study depends on the degree of successful filling of the microvascular system with the injection medium. An even greater disadvantage of these techniques is that they do not provide any information on the haemodynamics of the microcirculation. One can demonstrate a vessel but one must infer its function. The behaviour of the microvascular units during physiological function of the tissue they are in cannot be studied at all.

In recent years there has been an attempt to define the relative importance of the blood vessels reaching the tendon. Peacock (1959) on the basis of radioactive isotope (P^{32}) uptake concluded that "the blood vessels entering long tendons from the muscular origin and periosteal insertion are able to nourish only the proximal and distal third of the tendon. The intrinsic vessels in long tendons are not capable of nourishing the central third by anastomoses with vessels entering from either end. Circulation to the central third of long tendons is by intermediate segmental vessels entering through disorganized paratenon or a definite volar mesentery. Permanent disruption of the central blood vessels to normal tendons or mechanical prevention of post operative adhesions around free grafts, causes cellular death and eventual disintegration of collagen bundles". Smith in 1965 delineated the segmental nature of the blood supply more precisely. He stated, on the basis of silicone rubber compound injections, that the micro-circulation in tendons is segmental in nature and that a tendon freed from its segmental blood supply will only survive over a distance of 1–2 cm from its intact circulation. This conclusion, however, was based on the mere demonstration of vessels without an assessment of their function.

The recent advances in intra-vital microscopy allow for analysis of tissues and cells to proceed at a resolving level of 0.5 μ and sometimes even better (Brånemark 1966). Thus it is possible to observe simultaneously the microvascular system and the structure and function of the living tissue within which the microvascular system is found. It is possible to study the intricate and intimate relationship between capillary structure, capillary topography and flow pattern, and how this structure and activity of the terminal vascular bed is organized to meet the metabolic needs of the tissue.

The present investigation was designed in two parts. Part one was devoted to an assessment of the accuracy of morphologic demonstrations of the microvascular system of the tendon by means of clearing techniques and microangiography. Part two was devoted to intravital observations on the microvascular anatomy and microcirculation of the tendon.

MATERIAL AND METHODS

50 young rabbits (2–3 months of age) weighing approximately one kilogram were employed in this investigation.

Part 1. Microangiography and india ink injections

Microangiography was carried out as described by Lundskog and Brånemark (1968). India ink injections were carried out with commercially available india ink diluted with normal saline in the ratio of 1:5 and then filtered six times through Munktell filter paper No. 3. No measurements of injection pressures were carried out. Before injection the animal was heparinized. Injections were carried out through the femoral artery, aorta and where special emphasis was placed on the front paw, through a polyethylene canula inserted into the axillary artery. After perfusion with Micropaque® or india ink the animal was given an overdose of anaesthetic and then the whole animal was immersed in 10% formalin for 10 days.

Tendons subjected to microangiography were carefully prepared by micro-dissection to preserve the epitenon. Tendons injected with india ink were carefully dissected out preserving the paratenon, periosteum and muscle. The tendons were then cleared using the Spalteholz technique and, while immersed in the clearing solution, with the aid of the stereo dissecting microscope (Leitz), were carefully prepared with micro instruments to preserve the architectural pattern of paratenon and epitenon. Recordings were made with the Leitz-Wetzlar camera using objectives 16 mm, 1:2.5; 25 mm, 1:3.5; and 63 mm 1:4,5, with variable intensity diffuse transillumination and variable diaphragm openings of the objectives, to allow for adjustment of focal length and thus allow for different degrees of optical tissue penetrance.

Part II. Intravital Microscopy

All animals were anaesthetized using intravenous urethane and were tracheotomized. An attempt was made to carry out the intravital observations under as ideal conditions as possible (Brånemark 1959). All preparations were carried out using microsurgical techniques with the aid of variable magnification and filtered illumination with the infra red portion of the spectrum filtered out. Hemostasis was achieved either by application of saline soaked Spongostan® or with a microdiathermy unit (Brånemark 1964).

The exposed tendons were studied in the "Leitz Intravital Microscope" using both transillumination and incident illumination. For incident illumination the Ultropak objectives UO×3.8×6.5×11 and ×22 were employed. Photomicrographic recordings were made as described by Brånemark (1963) and with certain modifications thereof.

RESULTS

Part I. A. Microangiography

Microangiography proved to be an unsuitable method for the demonstration of tendon micro-vascular architecture. In spite of constant perfusion conditions, the filling of the vascular system with Micropaque was very variable. In addition, the kV and mA required for uneven tissues, "burned out" in some areas any microvascular portion of the system that was filled. These tendons were subsequently cleared by the Spalteholz technique and examined. A very variable filling of the small vessels was observed with frequent "embolic" phenomena. An attempt was made to use "Thorotrast" instead of "Micropaque". Although the study was carried out only in one animal, the necessity for immediate removal of the tendon with ensuing leakage of the "Thorotrast" from patent vessels does not suggest great promise for this technique.

B. India Ink Injections

With this method it was possible to achieve a much better filling of the micro-vascular system and more reliable studies could be accomplished. It must be emphasized, however, that despite filtering of the solution and heparinization of the animal, when such a perfusion was observed under the intravital microscope, frequent clumping with embolic phenomena occurred. This resulted in a variable filling of the microvascular system. Even if intravascular clumping of the particles did not occur, then only those capillaries were filled which were open while the perfusion was being carried out. Therefore, we did not attempt any detailed analysis of the microvascular system on the basis of this method. It was employed as a means of general survey of the vascular anatomy of the tendon in the rabbit.

The illustrations (Fig. 1, Fig. 2, and Fig. 3*a*, *b*) show that the vascular anatomy of the tendon in the rabbit conforms to the general pattern observed in man.

The lack of any uniformity in the vascular architecture of the epitenon circulation in different tendons and even in the same tendon was striking. (See Fig. 4 and compare it with Fig. 2 and 3.) Fig. 5 and Fig. 6 are segments of the same tendon showing an entirely different arrangement of the epitenon vascular architecture.

An attempt was made to analyze the relationship between the tendon mass and the spacial orientation of the vessels. In order to accomplish this we analyzed cross sections of thin flat tendons, such as the extensor digitorum communis distal to the musculotendinous junction but proximal to the extensor retinaculum, and thick round tendons such as the flexor carpi ulnaris. A definite correlationship was established. Thick round tendons in addition to their epitenon circulation have a number of vessels deeply situated in their substance (See Fig. 7, 8, and 9). In many instances it was possible to demonstrate the connections between the epitenon vessels and those in the substance of the tendon. (See Fig. 9, 10, and 11). Thin flat tendons on the other hand, have most of their vessels situated either in epitenon or very close to the surface in endotenon (See Fig. 12 and 13).

Part II. Intravital Microscopy

A number of tendons were examined before the extensor digitorum communis was chosen as the experimental model. These trials will be discussed because observations made during the search for a suitable tendon and a suitable method are pertinent to the discussion. The first tendon to be examined was the tendo-achilles. Although attempts at transillumination failed because of the thickness of the tendon, under the dissecting microscope at a magnification of 80× we observed a very rich epitenon circulation characterized by very similar repeating microvascular units fed by separate arterioles and draining into separate venules. We transsected the tendo-achilles at its mid and lower third with a micro-scalpel and used microdiathermy to control hemorrhage from the epitenon circulation. We found many punctate hemorrhages in the depth of both the proximal and distal stumps, which confirmed the presence of vessels within the tendon.

The next tendon to be examined was the tibialis anterior. In the rabbit the parietal tenosynovium surrounding the tibialis anterior at the ankle forms a large sac and contains a considerable quantity of synovial fluid. The extensor retinaculum is in the form of a thick fibrocartilageous band. We chose this tendon to avoid the problems

of the paratenon and hoped that in this fashion a segment of the tendon could be transilluminated with its "internal vascular supply" intact. The synovial tendon sheath and the fibrocartilagenous extensor retinaculum were opened. The tibialis anterior was transilluminated with its insertion intact, as well as transsected at its insertion and lifted out of its bed. We again failed to visualize any "internal vascular supply". This undoubtedly is related to the thickness of the tendon, the relatively poor contrast of living unstained tissues, and the inability to penetrate optically a thick translucent tissue with the intravital microscope.

The surface of the tendon, deep to the extensor retinaculum, was devoid of any vessels at the level of the ankle joint as this is a friction zone. A mesotendon reached the tibialis anterior on its posterior non-friction surface. This afforded an opportunity to observe the circulation in the mesotendon as well as in the epitenon on that side.

The mesotendon contained vessels of the order of pre-arteriolar arteries and small veins. The mesotendon was long and the vessels folded up in an accordion like fashion without any disturbance in the flow of blood. Stretching the mesotendon first produced a slowing of both the arterial and venous circulation, and at greater tensions the circulation came to a standstill. On reaching the epitenon the arterial vessel divided into a central ascending and descending branch from which at regular intervals on both sides arose arterioles which in turn gave rise to capillary beds. Each capillary bed drained towards the central vessel via many venules which, on reaching the center gave rise to one or two venae commitantes, one on each side of the arterial vessel. The capillary circulation had also many capillary anastomoses at its periphery joining each microvascular unit with its neighbour. Occasionally one could also see a branch of an arteriole dipping into the substance of the tendon.

The extensor carpi ulnaris was chosen as the next tendon. Because of its situation, once the paratenon was stripped, the tendon could be easily lifted out of its bed and by rotating the limb one could easily bring this tendon between the condenser and the objective of the microscope. This tendon was thin. There was no problem with transillumination or optical penetration of the tissue. Yet, we failed to identify a single vessel except in the region immediately adjacent to the musculotendinous junction where the circulation appeared intact.

The extensor digitorum communis is a long flat tendon which only narrows and becomes round close to the extensor retinaculum. In its proximal portion, immediately adjacent to the musculotendinous

junction, to the naked eye it appeared as a single tendon. Under the dissecting microscope, however, even at this level, four discrete tendons, thin and flat, all enveloped in a glistening transparent paratenon could be identified. More distally the identity of each tendon become more obvious. These tendons are so arranged that in their proximal portion they slightly overlap each other, with the most lateral (radial) one being most superficial.

A window was made in the lateral aspect of the paratenon and a prism 1 mm × 1 mm and 3 mm in width attached to a fibre optic was introduced under the tendon. In this way transillumination of a tendon in paratenon could be achieved. (See Fig. 14.)

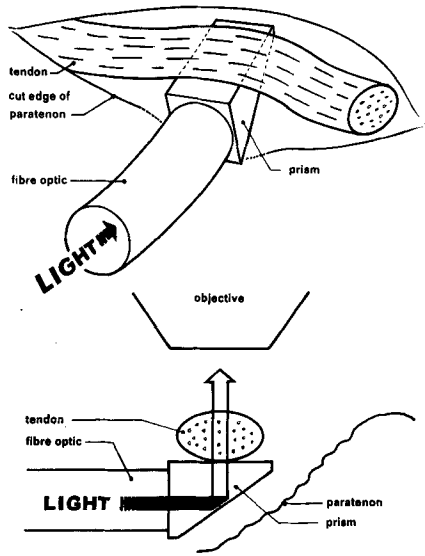

Fig. 14. Illustration of transillumination of a tendon with a fibre optic and prism.

Only large arterioles and venules could be demonstrated. The circulation was obviously impaired. The preparation was very sensitive to the extent the paratenon had to be freed to allow for the introduction of the prism under the tendon and also to the stretching of the tendon over the edge of the prism. The prism was modified. A plexiglass rod was employed (See Fig. 15). The end was ground to a flat disc, 5 mm in diameter and 1 mm in height. In the center a groove was cut 3 mm

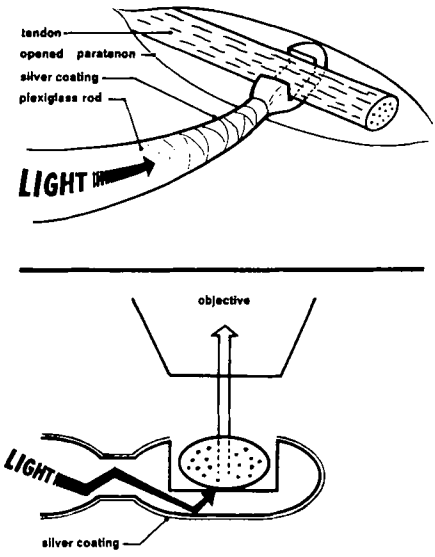

Fig. 15. Illustration of transillumination of a tendon with a ground plexiglass rod.

wide and ½ mm deep. By manipulation the freed tendon was slipped into the groove and transilluminated. Again only arterioles and venules with grossly impaired circulation could be demonstrated. We observed, however, that in incident illumination with most of the paratenon intact, a rich capillary circulation was present in the tendon. This observation led to the development of our present experimental model.

The paratenon and perimysium were carefully removed by means of microdissection from the exposed surface of the tendon and muscle respectively, preserving every vessel. The specimen was examined in incident light illumination with the ultropak equipment (See Fig. 16).

We observed long and tortuous vessels in the paratenon interposed between the deep fascia and the tendon, as well as paratenon vessels which reached the tendon from the side and on its under surface. These paratenon vessels were both arterial and venous. The arterial vessels on reaching the tendon divided first into smaller vessels, which then give rise to a capillary plexus (See Fig. 17). Our area of observation was limited to the musculotendinous junction and to the flat portion of the tendon. Where the tendon become round and passed beneath the extensor retinaculum, it was in tenosynovium and had no surface vessels present, as this is a friction zone.

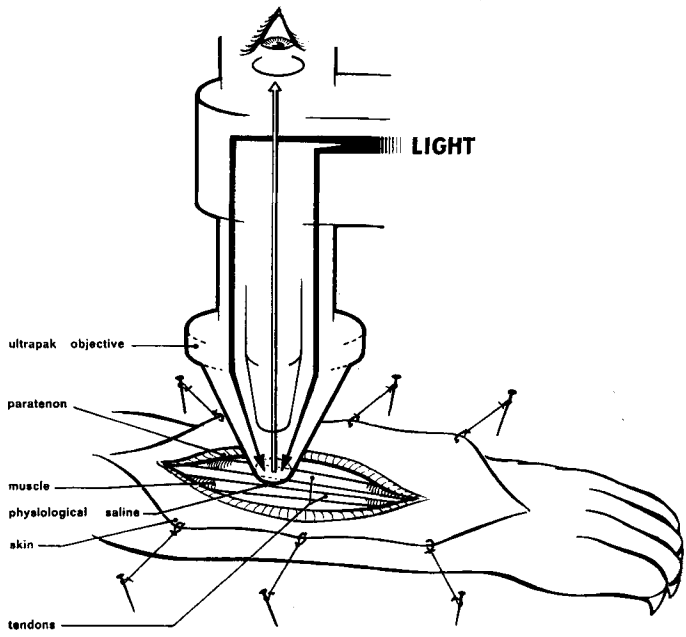

Fig. 16. Illustration showing the method of intravital observation of the tendon circulation using incident illumination.

A. The Musculotendinous Junction

Observations carried out on the musculotendinous junction have disclosed the following (See Fig. 5).

(1) The microvascular architecture of the muscle and of the tendon differ not only in their pattern but also show no communication. The muscle capillaries run a straight course along the sarcomeres (See Fig. 18) and where these join the tendon, the capillaries loop back to rejoin the muscle circulation (See Fig. 19).

(2) There are a number of vessels which cross the musculotendinous junction. These vary in size, are quite superficial, and are both arterial and venous, although the veins do appear to be predominant.

B. The Tendon in paratenon

There were a number of longitudinal vessels which ran in the long axis of the tendon. Unfortunately, most of these were too deep to be resolved with any detail using incident illumination. Flow directions

in these vessels were both proximal and distal, but on this basis alone it was impossible to conclude which was arterial and which was venous.

Arterioles appeared in random fashion close to the surface of the tendon and gave rise to the following types of microvascular units.

(1) There were capillary loops which ran for long distances parallel to the tendon bundles, then looped back, traversed an even longer distance again parallel to the tendon bundles before looping back again to join a venule. One arteriole gave rise to more than one capillary loop, and by focusing up and down, it was possible to discern that these were in different planes of the tissue (See Fig. 20 and Fig. 21).

(2) There were regions where the microvascular architecture appeared to be less specialized and resembled that of the hamster's cheek pouch (See Fig. 22 and Fig. 23).

(3) There were also regions where the capillaries were very short, ran a straight course and immediately joined a venule. This suggested that they may function as shunts.

In all capillaries (See Fig. 24), high flow velocities have been observed. The velocities were so great that erythrocytes could not be identified as discrete particles with visual observation. This suggested a flow velocity of at least 1.0–1.5 mm/sec. Reversal of flow in the capillaries has been observed, as well as vasomotion.

We subjected the tendon circulation to a number of manipulations.

Trans-section of the Tendon at the Level of the Carpus

(1) Once the tendon was cut, it immediately assumed a wavy pattern, but no observable changes took place in its circulation in the exposed region which was being continuously observed.

(2) *Trans-section of the Tendon at its Musculotendinous Junction.*

This manouver was associated with considerable hemorrhage. The circulation in many of the longitudinal vessels stopped, but the regional capillary circulation except that immediately adjacent to the cut appeared unaffected.

(3) *Isolation of a Segment of Tendon by Proximal and Distal Trans-section Maintaining the Paratenon Intact.*

Immediately following the trans-section all circulation in the tendon often came to a stand-still. In some areas pulsatile movement of the

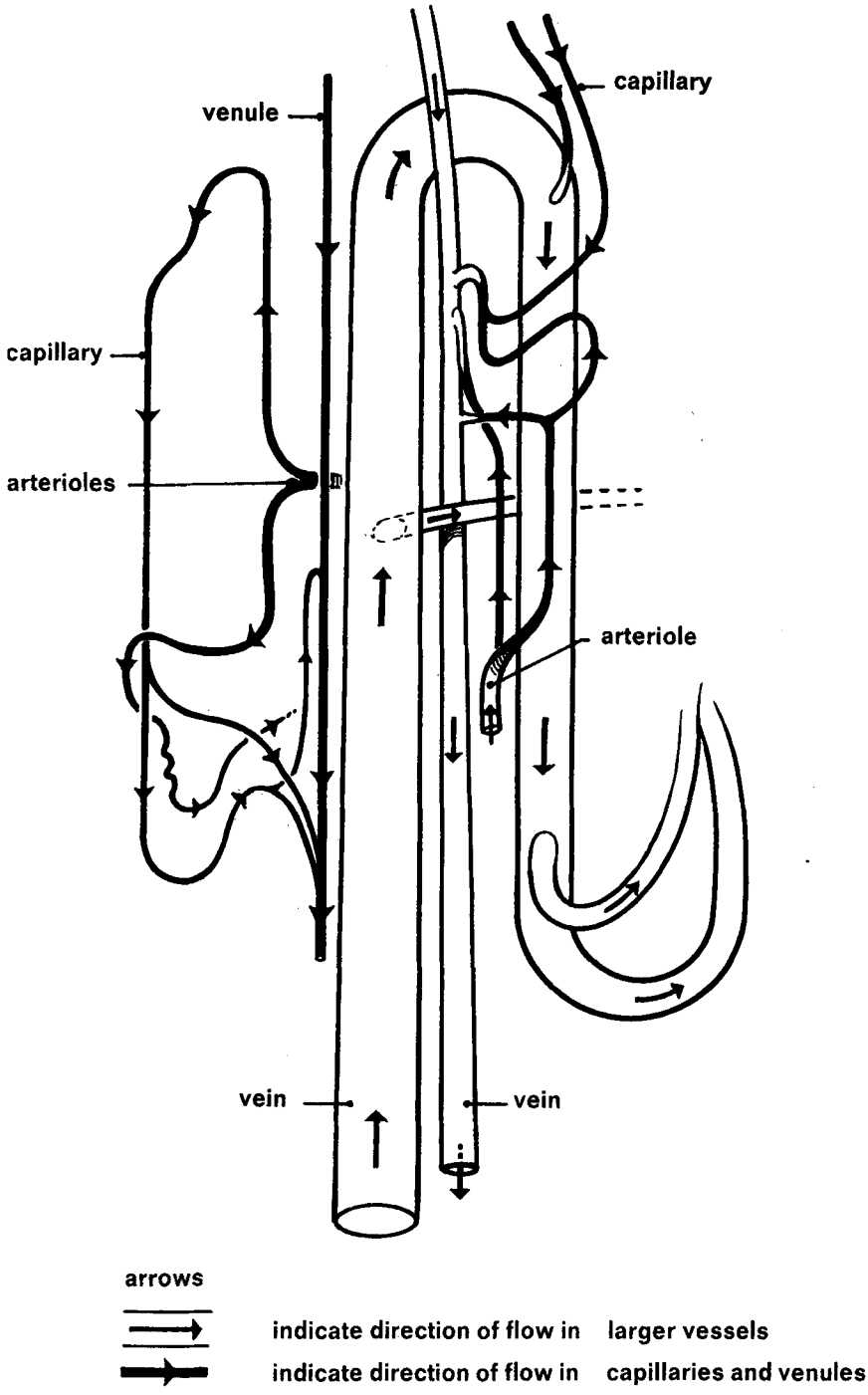

Fig. 20. Diagram illustrating the long loop capillary pattern in tendon.

blood column occurred. Within one to two minutes however, most of the arteriolar, capillary, and venular circulation in the isolated segment of tendon was resumed often sluggishly at first, but it soon returned to its former vigour (See Fig. 25).

(4) *Trans-section of the Tendon Distally and Application of Varying Degrees of Tension.*

As previously stated, distal trans-section had no influence on the circulation proximally. As greater and greater tension was applied changes could be observed. At first the venous circulation slowed down, then the capillary, until finally flow ceased altogether. On releasing the tension, the flow was immediately resumed.

(5) *Tendon Lymphatics.*

We have attempted to repeat Edwards (1946) method of lymphatic channel demonstration. He cautioned that the preparation must be fresh to succeed. Our preparation was alive. We observed all the technical points, and yet failed to get a single preparation.

In addition, methylene blue was deposited in the tendon distally in the hope that with time and exercise the dye would be taken up by the lymphatics. Up to six hours no dye was observed proximally in the tendon.

DISCUSSION

The literature abounds with the term "The Blood Supply to Tendons" without regard to the tendon in question. Berkenbusch (1887) studied the flexor tendons within flexor sheaths. Rau (1914) based his observations on the infrapatellar tendon and the tendo-achilles. Edwards (1946) studied the flexors and extensors crossing the metacarpals and metatarsals. Arai (1907), Dychno (1936) and Smith (1965) have studied the tendons in the whole extremities. Similarities do exist, but it is only on similarities that generalizations can be based.

There are many variations in the arrangement of vessels even within a single tendon, which have to be considered if a meaningful functional analysis of tendon circulation is to be established.

It is important to draw clear distinction between endotenon, epitenon, tenosynovium and paratenon because this not only gives precise anatomic localization, but also identifies regions of the tendon subjected to different local mechanical situations which determine the manner of the

blood supply to the tendon. Thus in paratenon where the relative amplitude of displacement of the tendon in relationship to the immediately adjacent tissue, the paratenon, is negligible because the paratenon moves with the tendon, vessels can reach the tendon in a random fashion, where the relative amplitude of displacement of the tendon in relationship to the immediately adjacent tissue is great because the tissue is fixed such as a pulleyan, a retinaculum or fibrous tendon sheath the blood vessels reach the tendon on its non friction side in a specialized structure, the mesotendon. Although we have found the injection techniques not sufficiently accurate for the demonstration and study of the microvascular units they serve well for the demonstration of larger vessels and for the study of their spacial organization. On the basis of our injection studies we have demonstrated that the spacial organization of blood vessels of tendons is related to the size of the tendon. Thin flat tendons tend to have most of their vessels arranged superficially in epitenon, whereas thick round tendons have both a superficial and a deeper internal blood supply. It is for this reason that we feel that the epitenon circulation cannot be divorced from the tendon circulation proper because it takes part in supplying the metabolic needs of the tendon. This superficial and deep arrangement of vessels also suggests that there must be a critical distance between a microvascular unit which is the metabolic exchange zone and the tenocyte, or that there is a relationship between a specific mass of tendon tissue and the spacial orientation of the microvascular units. As yet we have been unable to define this relationship, but feel that the concept of Edwards (1946) and Brockies (1953) of a simple uniform system of vessels throughout with frequent and regular cross anastomosis is a gross over-simplification. We have demonstrated in vivo three types of microvascular units which are not evenly or constantly distributed. The function of the longitudinal "intrinsic" vessels still remains obscure. They are incapable of supporting long segments of tendon whether it is in paratenon or tendon sheath (Potenza 1959, Peacock 1963, Smith 1965). We have not been able to observe any circulation in the longitudinal vessels of tendons completely stripped of their paratenon blood supply. In tendons with only partially disrupted segmental paratenon blood supply the circulation in the longitudinal vessels was impaired. In an isolated segment of tendon with the paratenon vessels intact the microvascular circulation was intact but the flow in the longitudinal vessels was interrupted. This would suggest that they may be only venous channels, and for this reason of course are unable to maintain a tendon viable

which has been isolated from its segmental arterial blood supply.

The fact that the blood supply to tendon is segmental may have definite bearing on certain clinical therapeutic manouvers. Brånemark et. al (1967a, b), and Goldie (1967) showed that certain suspension media of corticosteroids completely arrest capillary blood flow. One of the authors (J.S.) has knowledge of two patients whose tendoachilles were injected for "crepitant tenosynovitis". Within two weeks the patients sustained "spontaneous" ruptures of their tendo-achilles. It is likely that local necrosis of the tendo-achilles occurred and as this tendon has to withstand tremendous tensile stresses, it ruptured in the necrotic area.

We have adequate data to dispel certain long held concepts in tendon surgery. Hall (1965) writes: "There is some purpose in distinguishing between a tendon transfer in which vascularized tendon is moved from its normal point of attachment and inserted into an adjacent area and tendon transplant in which the whole tendon is made avascular".

Every manouver which separates the tendon from its segmental paratenon or mesotendon renders the tendon avascular. This not only explains why adhesion formation occurs, but also why blocking interposition substances are doomed to failure. In tendon transfer sharp angulation, point pressure and excessive tension must also be avoided, for they embarrasses the tendon circulation.

Intravital observations in incident light are limited to the superficial layers of tendon only. Thus only the micro-vascular units in the epitenon and in the most superficial layer of the tendon could be studied. However, as the epitenon circulation is part of the blood supply to the tendon and in thin flat tendons such as the one studied most of the vessels were disposed superficially we employed this technique as a "biological window" into the behaviour of the micro-vascular system of the tendon.

Our data on the micro-vascular anatomy of the tendon is not adequate to allow for any further conclusions. We have established an experimental model and have made certain preliminary observations.

We are continuing our investigations and hope to present in the future a more comprehensive analysis of tendon circulation.

SUMMARY

1. A review of the literature dealing with tendon circulation is presented.
2. Different techniques for the study of tendon circulation are evaluated.

3. A method for the intravital study of tendon circulation is presented.
4. Conclusions:
   a) Injection techniques are not adequate for the study of the micro-vascular units of tendon circulation.
   b) There must be a critical ratio between available micro-vascular exchange surface area and mass of tendon tissue.
   c) The blood supply to tendons is segmental whether the tendon is in paratenon or tenosynovium.
   d) Any surgical manoeuver which frees the tendon from its paratenon or mesotenon devitalizes that segment of the tendon.
   e) The possible relationship between "spontaneous" tendon rupture and corticosteroid injection is presented.
   f) The influence of tension and compression on the tendon circulation is evaluated.

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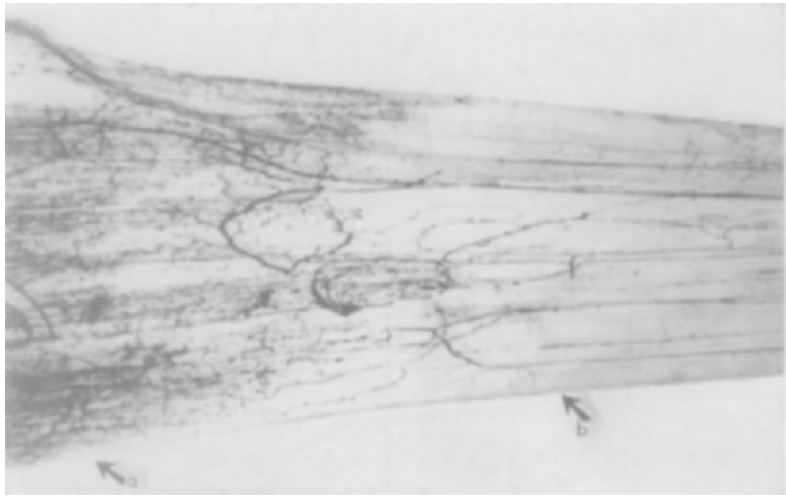

Fig. 1. The musculotendinous junction. Extensor digitorum communis. Muscle and tendon slip to longest toe. Observe the following: (i) The number of longitudinal vessels of variable diameter which traverse the musculotendinous junction. (ii) The discrete looping back of capillaries supplying the sarcomeres. (iii) The striking difference in the number of vessels present in muscle and tendon. (iv) The different architectural arrangement of vessels in the muscle and those in the tendon. (a) muscle; (b) tendon. Magnification $\times 23$.

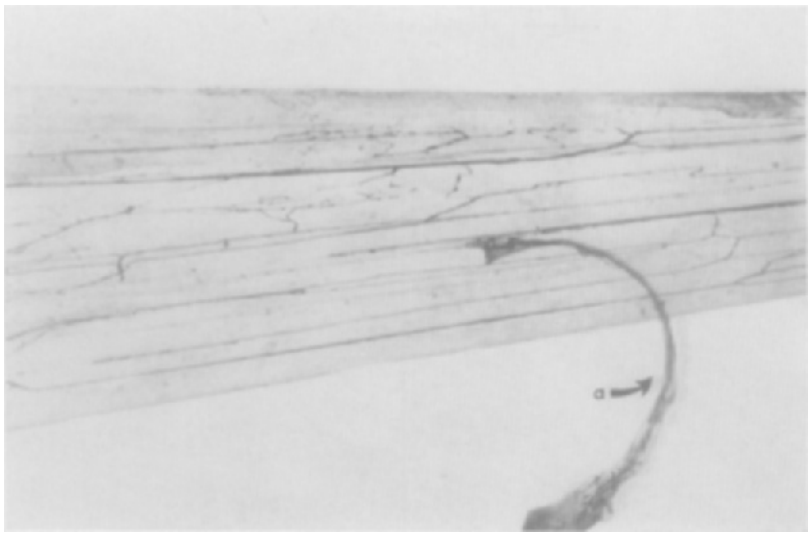

Fig. 2. Segment of the same tendon as in Fig. 1 with preserved paratenon vessel (a) joining the circulation of the tendon. Observe also the general arrangement of the vessels in the tendon which conforms to that previously described in man. Magnification $\times 25$.

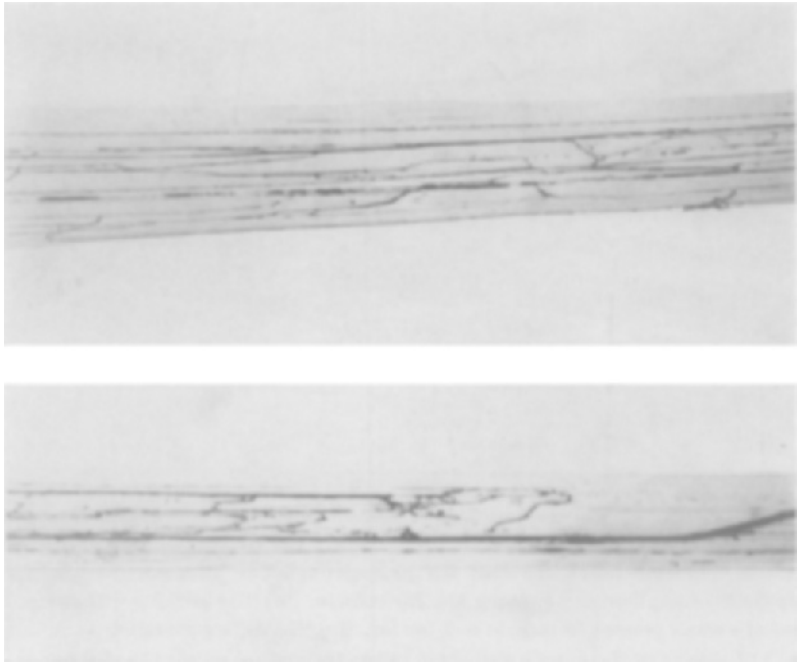

Fig. 3*a*) & *b*). Different segments of the extensor digitorum communis tendon taken proximal to the extensor retinaculum. Again observe the similarity in the architectural arrangement of the vessels. (*a*) & (*b*) are arranged in a proximo-distal order. Magnification ×15.

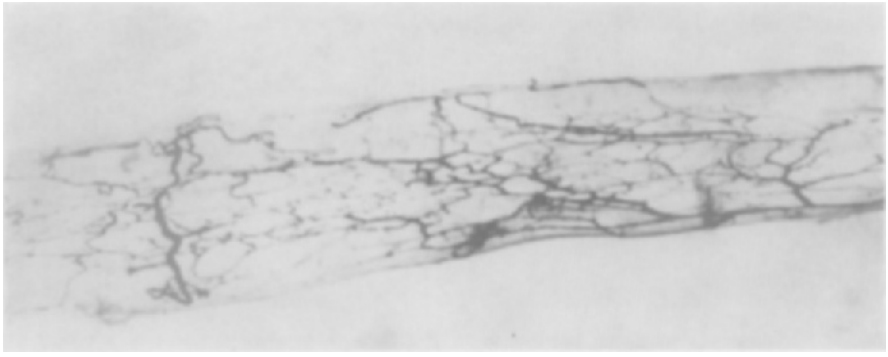

Fig. 4. Extensor digitorum communis. Segment in the region of the extensor hood. Picture focused on the superficial vessels. Magnification ×15.

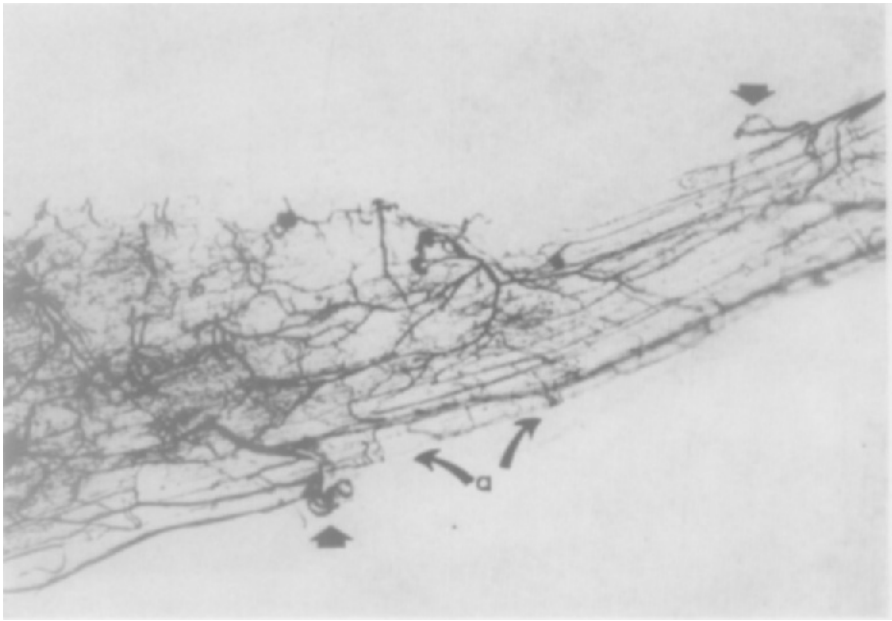

Fig. 5. Flexor digitorum communis. Observe the arrangement of the epitenon vessels (a) just distal to the musculotendinous junction. At arrows preserved paratenon vessels are evident. Magnification $\times 20$.

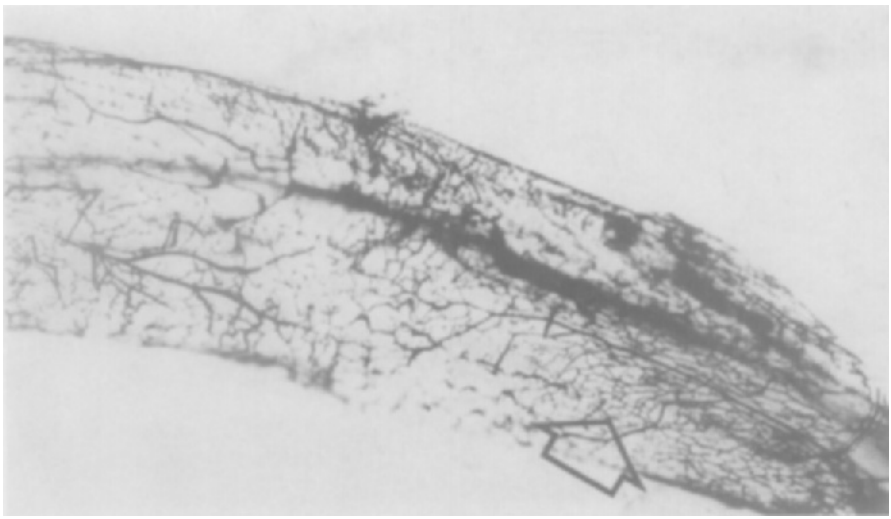

Fig. 6. Flexor digitorum communis. Segment proximal to the transverse carpal ligament. Note the profuse epitenon vasculature (arrow) and how it differs from Fig. 5. Under the stereo dissecting microscope it was possible to follow vessels from this profuse epitenon vasculature into the depth of the tendon. Magnification $\times 35$.

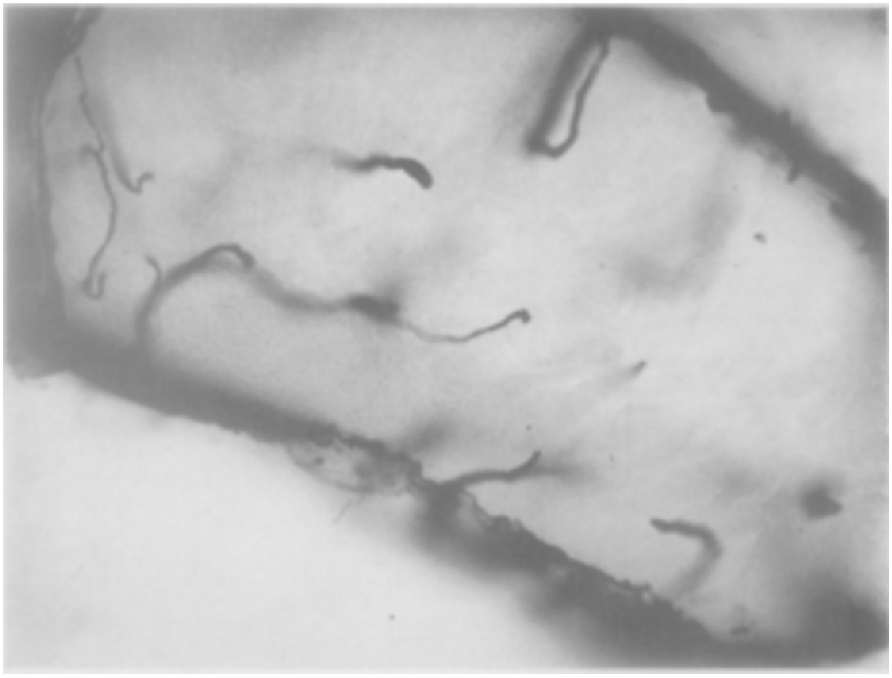

Fig. 7. Cross section of a thick round tendon demonstrating the presence of vessels deeply situated in the substance of the tendon. Magnification $\times 30$.

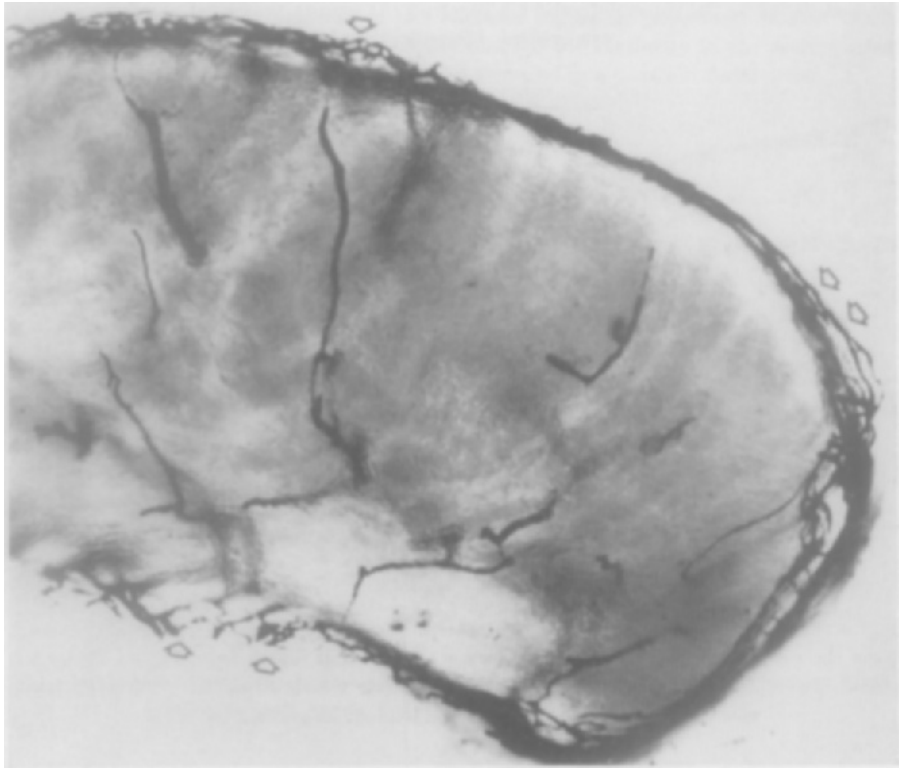

Fig. 8. Cross section of a thick round tendon demonstrating the presence and ramification of vessels deeply situated in the substance of the tendon, the epitenon vessels.

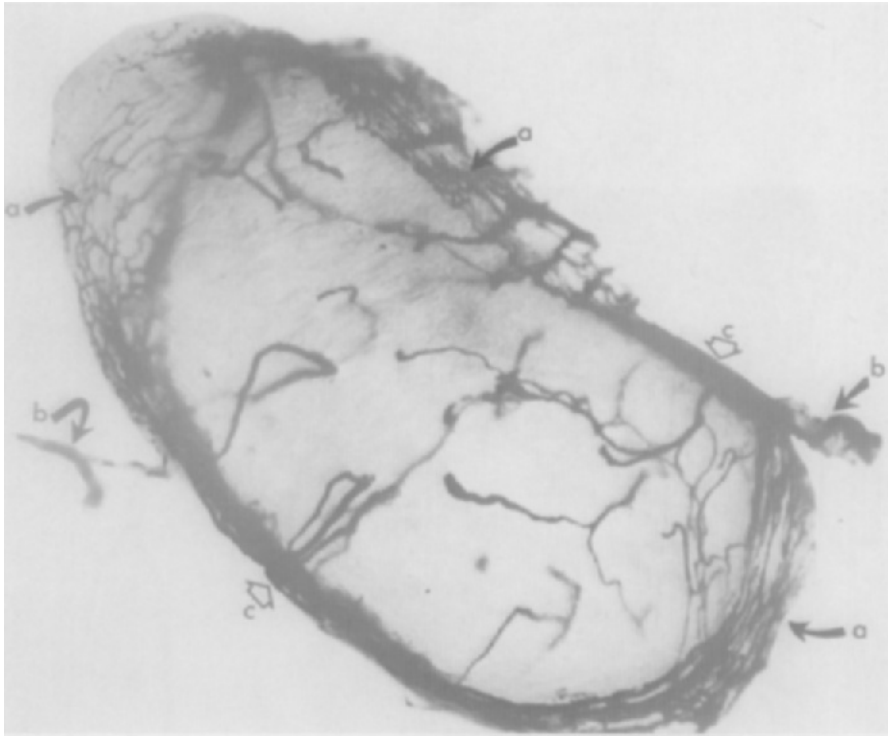

Fig. 9. Cross section of a thick tendon. Photograph taken at a slightly oblique angle. Observe: (a) the epitenon vessels. (b) the preserved paratenon vessel. (c) the connections between the epitenon and the deeply situated vessels. Magnification $\times 20$.

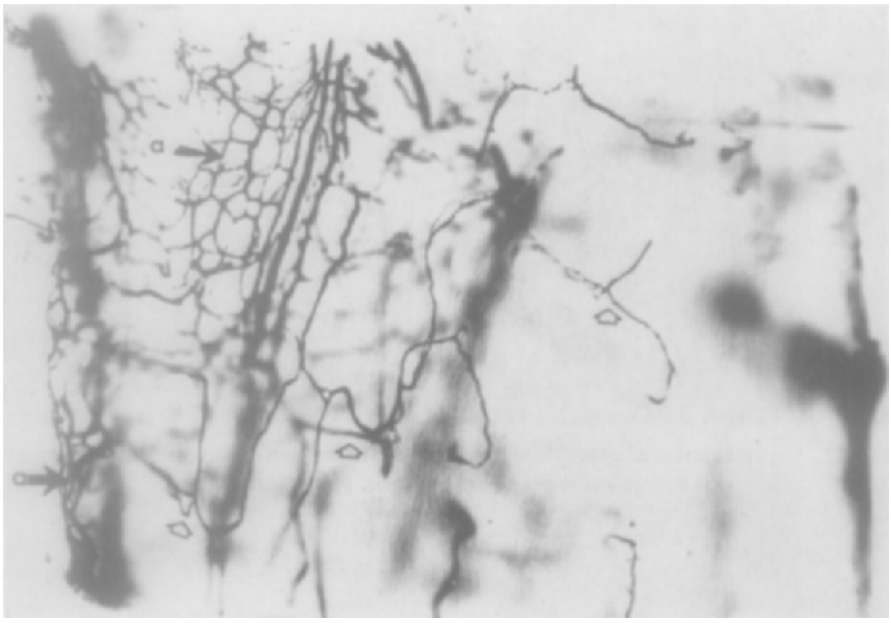

Fig. 10. Sagittal section of a thick round tendon. Observe the epitenon vessels (a) and the ramifying vessels in the depth of the tendon (open arrows). Magnification $\times 23$.

Fig. 11. Sagittal section of a thick round tendon. Note the connection between the epitenon and endotenon vessels (open arrows). Magnification $\times 50$.

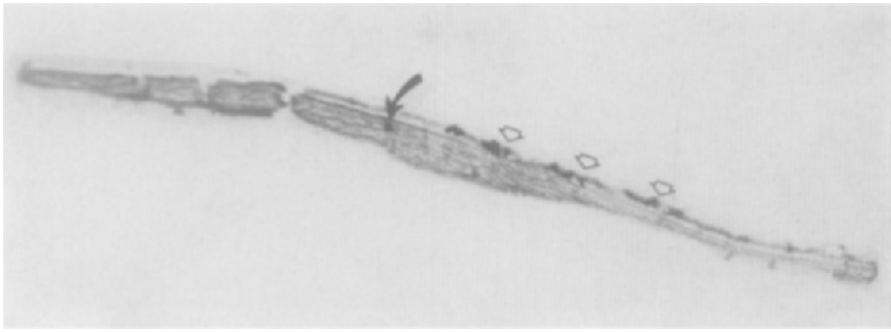

Fig. 12. Cross section of thin flat extensor digitorum communis tendon. The black dots are the vessels in cross section (open arrows). There is only one vessel in the depth of the tendon (closed arrow) and even this one is close to the surface. Magnification $\times 50$.

Fig. 13. Cross section of extensor digitorum communis tendon closer to the extensor retinaculum where the tendon becomes thicker and round. Note the appearance of vessels in its depth (arrows). Magnification $\times 65$.

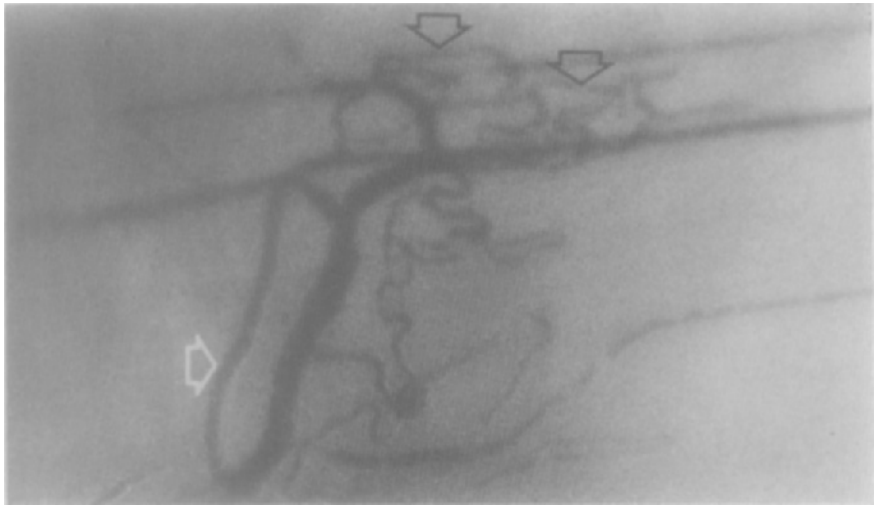

Fig. 17. The Paratenon Vessels.

Fig. 17*a*. Note that upon reaching the tendon the paratenon vessels (white arrow) divide, giving rise to progressively smaller vessels until a capillary plexus is formed (open arrows). Intravital photograph. Magnification $\times 100$.

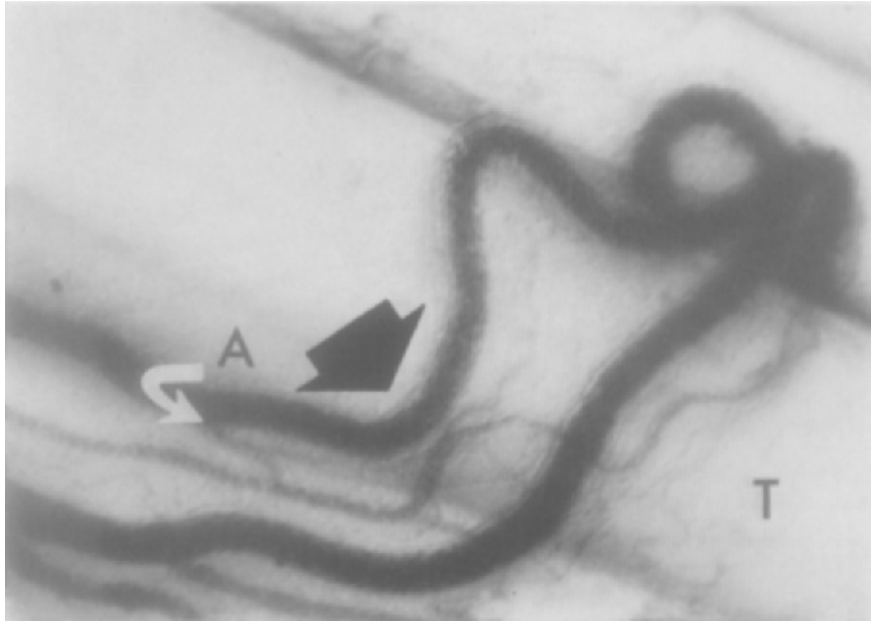

Fig. 17*b*. Note that the large vessels (closed arrow) are in paratenon and run in this tissue between tendons. Arterioles arise from the paratenon vessel when it is still large (open arrow) and go directly to the tendon. Intravital photograph. Magnification $\times 100$.

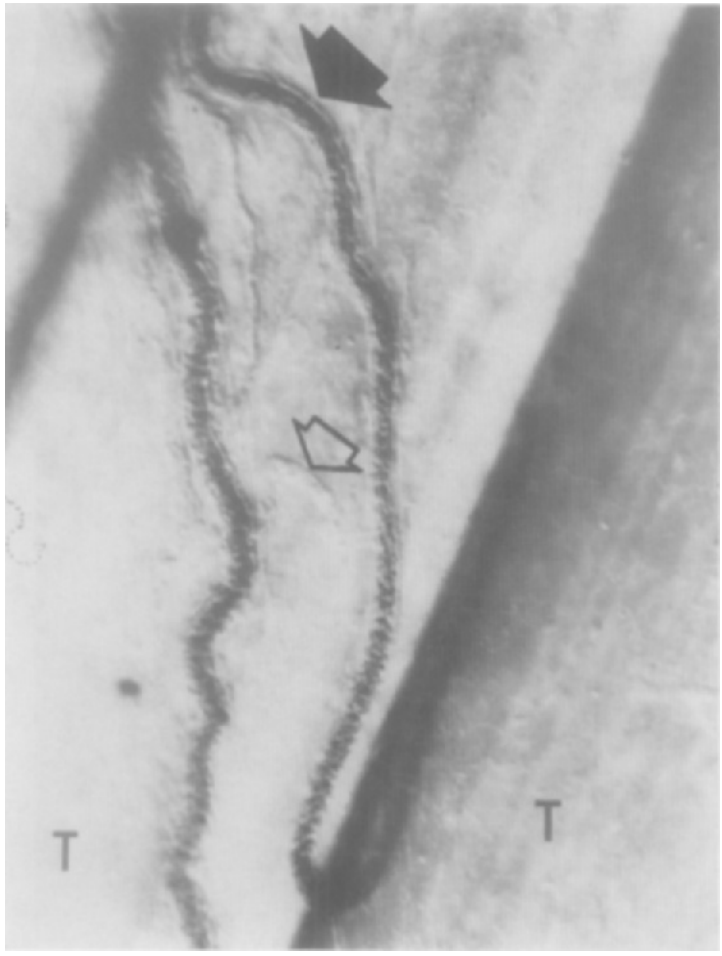

Fig. 17*c*. Note a capillary (open arrow) from the tendon (T) draining into a paratenon vein (closed arrow). Intravital photograph. Magnification ×125.

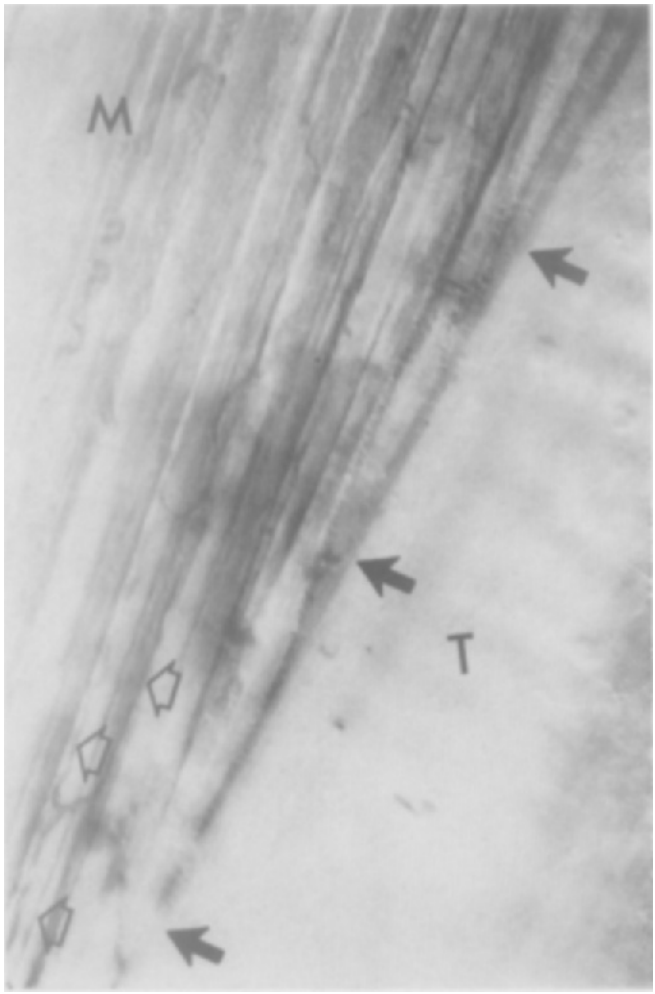

Fig. 18. The musculotendinous junction. Muscle M. Tendon T. Note that the muscle capillaries (open arrows) run along the sarcomeres. Note also the sharp separation between muscle and tendon (closed arrows). Intravital photograph. Magnification $\times 275$.

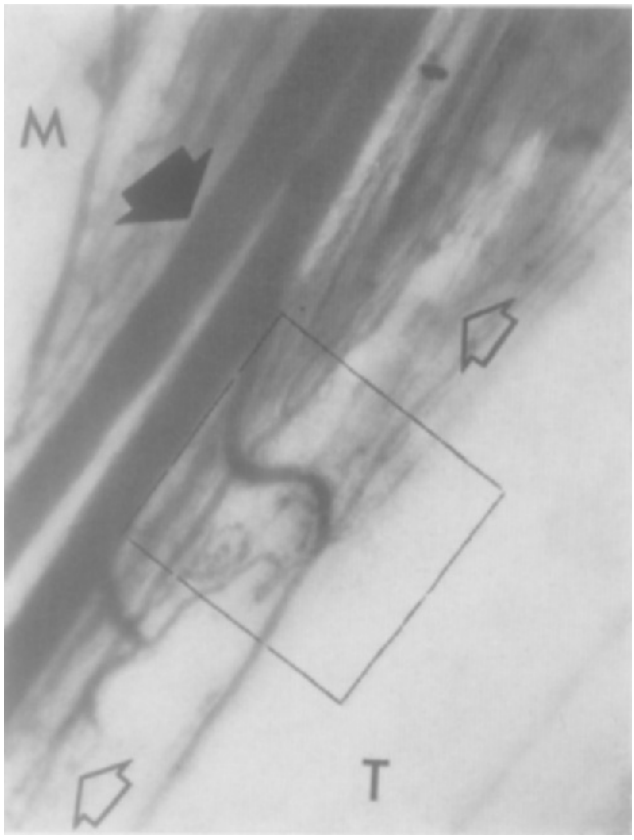

Fig. 19. The musculotendinous junction.

Fig. 19a. Note that the capillaries which supply the sarcomeres (open arrows) loop back and that there is no capillary anastomosis between muscle and tendon. The larger vessels (closed arrow), traverse the musculotendinous junction and continue into the tendon. Muscle—M. Tendon—T. Area in square magnified—see 19*b*. Intravital photograph. Magnification ×150.

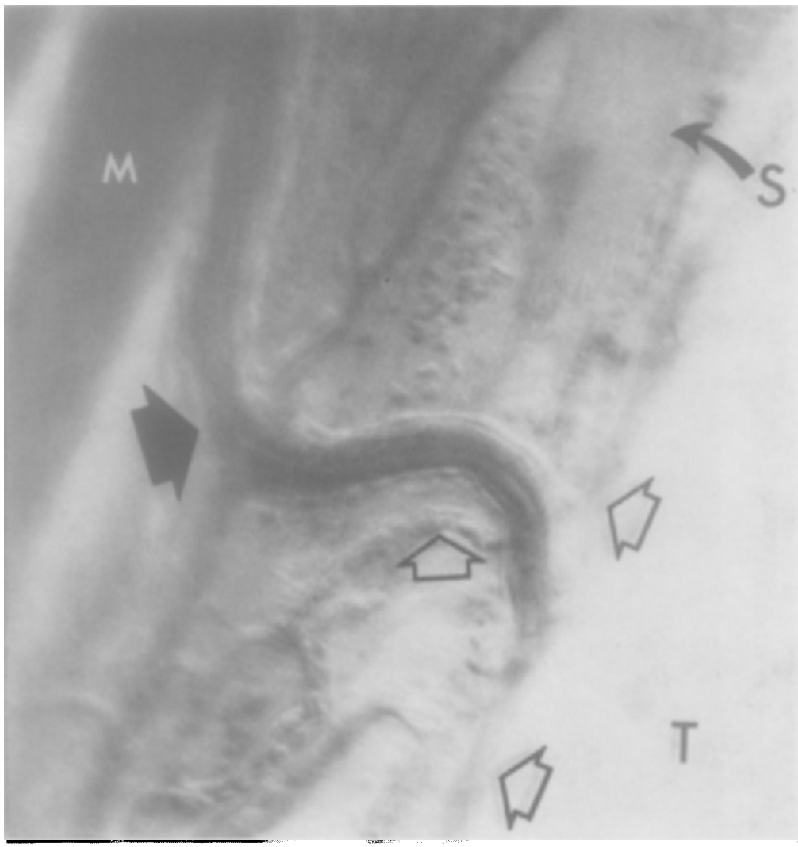

Fig. 19*b*. Note the arteriole in perimysium (closed arrow) giving rise to capillaries (open arrows) which supply the sarcomeres. There is no capillary anastomosis between the muscle (M) and tendon (T), the two capillary systems being quite separate. Note also the cross striations in the sarcomere (S). Intravital photograph. Magnification ×500.

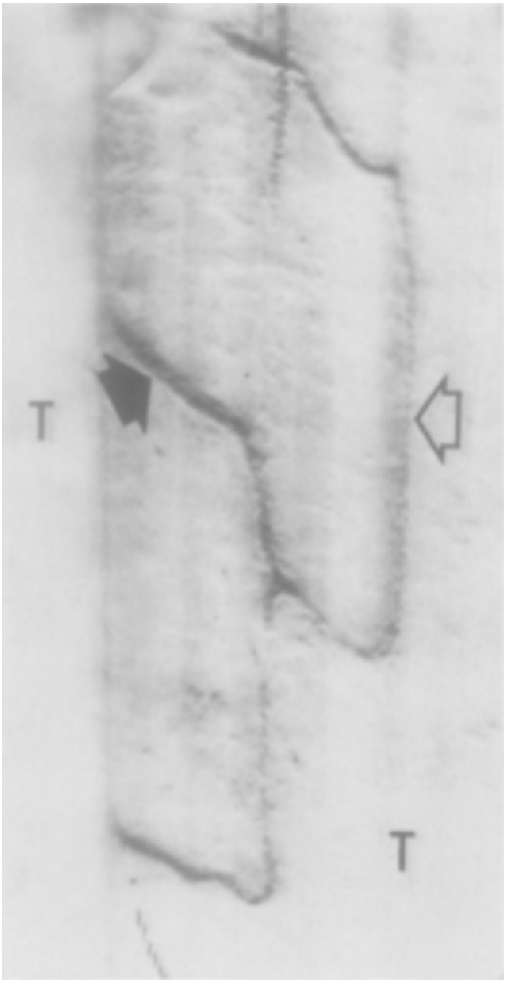

Fig. 21. Intravital photograph of the long loop capillary pattern in tendon. Open arrow—capillary. Closed arrow—arteriole. T—tendon. Magnification ×100.

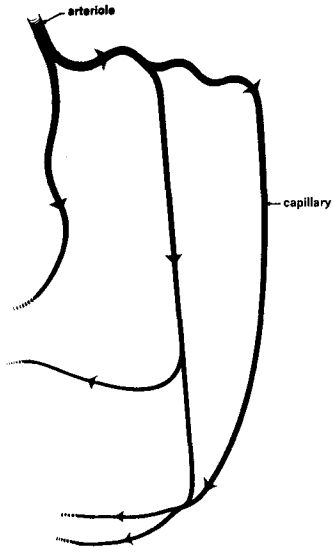

Fig. 22. Diagram illustrating the less specialized microvascular unit in tendon.

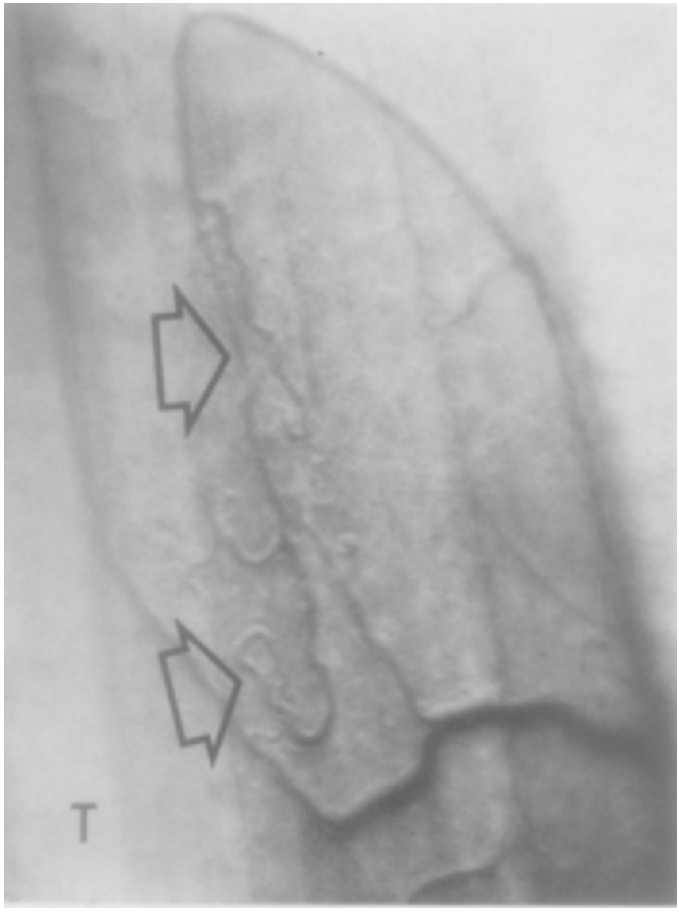

Fig. 23. Intravital photograph illustrating the less specialized microvascular units (open arrows) in tendon—T. Magnification $\times 100$.

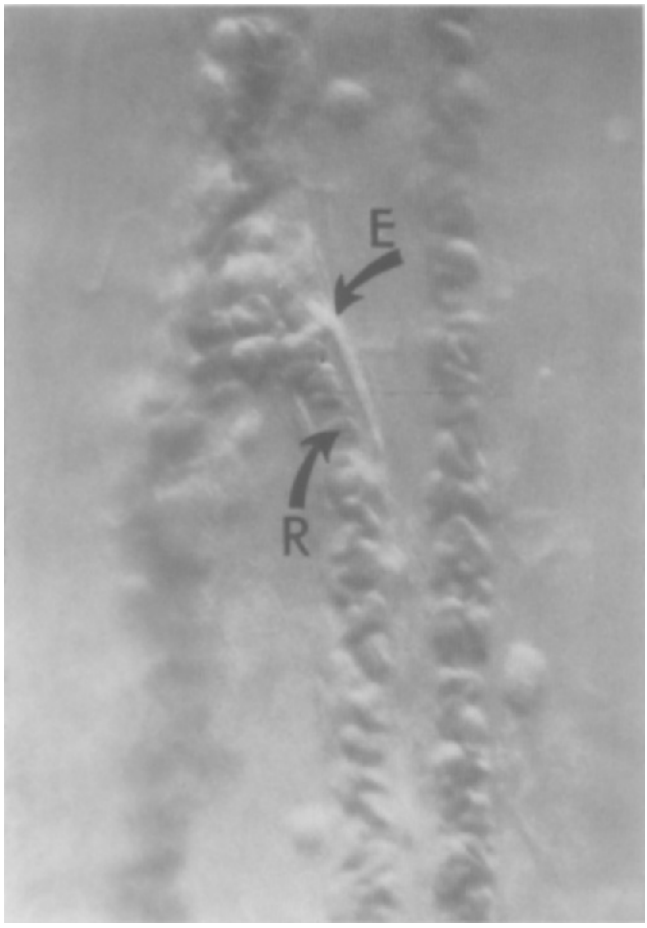

Fig. 24. Tendon capillary. Observe the discrete endothelial lining of the capillary (E) and the single row of erythrocytes (R). Intravital photograph. Flow rate slightly reduced. Magnification $\times 750$.

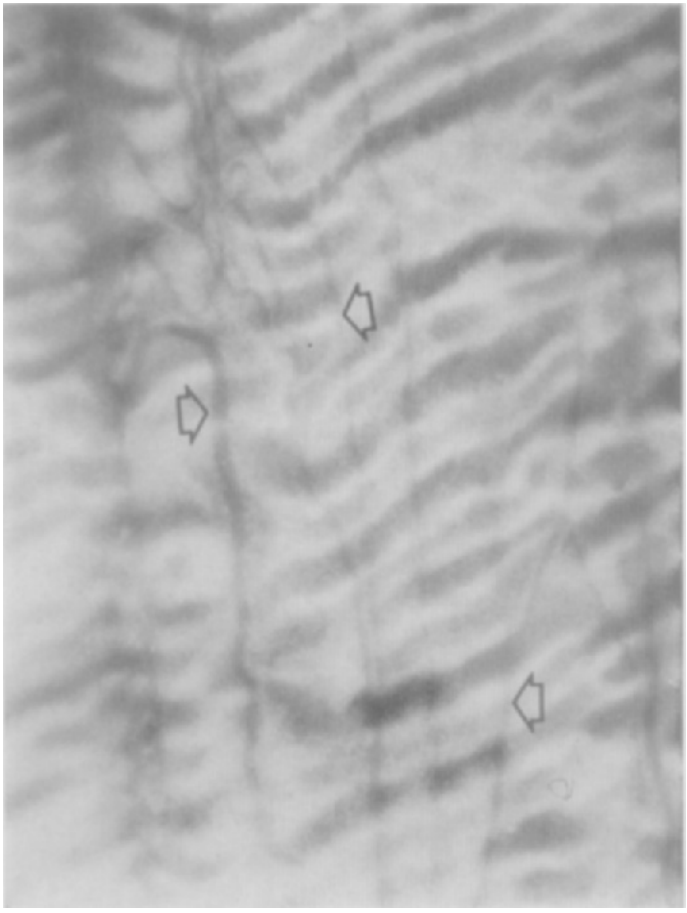

Fig. 25. Isolated segment of tendon with its circulation preserved. Note the waviness of the tendon. This waviness appears immediately upon proximal or distal transsection of the tendon. The vessels (open arrows) are not well demonstrated because of the different focal planes they assumed due to the waviness. Magnification $\times 100$.