PhD Theses

Experimental and clinical investigations of the possibilities for the reconstruction of flexor tendon injuries

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1. Introduction:

Restoration of the flexor tendon system after tendon injury within the digital sheath still remains a major problem in hand surgery. Especially difficult the problem if the flexor tendon reconstruction not a primary one. For digits that are classified pre-operatively as being in poor condition, that is, badly scarred, having residual joint stiffness, or with severe bone and soft tissue damage, the outcome after repair is disappointing; this applies as well to reconstruction for salvage of a failed flexor tendon repair. Single stage reconstructive techniques are lacking for the treatment of these injuries, and the most widespread method available and accepted is a staged flexor tendon reconstruction.

In the reconstruction of the flexor tendons we are using tendon grafts in different forms.

At the beginning of the twentieth century being done a lot of work especially in Germany by Lange, Kirschner, Rehn and Biesalski.

Bunnell in San Francisco turned his interest more toward surgery of the hand. Between the time of his first article on tendon repair in the fingers, published in 1918, and his book from 1944, he had formulated the principles that now form the basis of tendon surgery.

At that time, primary suturing of flexor tendons was almost always doomed to failure in the digital canal. Although the tendon healing was usually satisfactory, adhesions were so extensive that tendon mobility was nil. In the face of such consistently poor results following primary suturing in what he called “no man’s land” in 1922 Bunnell gave his advice: “ Close the skin, wait for the wound to heal, then perform a secondary repair as follows: excise the two flexors and graft the profundus tendon alone from the lumbrical to the digital extremity”.

This teaching was held as a dogma by generations of surgeons (Boyes, Pulvertaft, Graham, Littler, Tubiana) for the treatment of laesions within “no man’s land”.

Tendon grafting is an ingenious attempt at solving some of the biologic problems of tendon repair. Not only can a tendon graft compensate for a loss of a

substance, but it also offers the advantage that the sutures are tension-free and can be placed in an optimal position, away from the fibrous pulleys, and the digital sheath.

In practice, most grafts are autogenous. The possibility of using preserved grafting materials has been considered for long time. This would allow the creation of tendon banks and obviate the need for autogenous graft.

Restoring or reconstructing the flexor tendon sheath after tendon repair has been an important step forward. The attitude toward the flexor sheaths has changed considerably over the years. For a long time the tendency was to resects much of the sheaths as possible and to preserve only narrow pulleys. The reasoning was that the sheaths formed a barrier against vascularisation of the graft and there was a risk of the grafts becoming adherent to the fixed structure. Since the studies of Peacock, Potenza, Lundborg, Matthews, Doyle and Blythe. Manske and many others the mechanical and nutritional actions of the digital flexor sheath are better understood. The most important pulleys must be reconstructed around the graft.

In 1959 Carroll and Bassett used silicone rods to induce pseudosheath formation. Since 1960, Hunter has progressively developed a two-stage procedure using a silicone rod for preliminary preparation of a pseudosheath. The basic concept of this technique is that when a pseudosynovial sheath is formed in response to a biologically inert implant, the cells adapt so that they can effectively accept the tendon graft.

On the other hand the territory of the digital sheath is not really well known. Further investigations are necessary to achieve a better result in the treatment. For this investigations is absolutely mandatory an animal model, on which the new methods, the different surgical procedures are possible to perform. This model should be very similar to the human hand, should be cheep, and the experiments should be reproducible in any place. Previous reports described the chicken foot as a valuable model for flexor tendon research.

2. Aims of the study:

Our goal was in the present study, to understand the anatomy and function of the flexor tendon system of the third (long) toe of the chicken feet, and their application in the clinical practice.

2.1. We were interested not only for the anatomy of this system, but for the differences between the flexor system of the chicken feet and human hand.

2.2. We investigated not only the macroscopic differences, but the histological, and ultrastructural findings as well.

2.3. We do believe these investigations can help to introduce a new model for the bio-pathology of the flexor tendon system.

2.4. Our findings can help in the introduction of new methods in the flexor tendon reconstruction, especially in the reconstruction of those fingers that were classified preoperatively as poor.

The next papers are attempts to achieve the aforementioned goals, and the introduction of the results in the clinical practice.

3. Anatomy of the chicken foot for the experimental investigations in flexor tendon surgery

The chicken is a convenient model for experimental tendon studies, since all of the critical structures of the human flexor tendon system are present in the chicken foot. The experimental results are reproducible and the research subjects are inexpensive.

Although chickens have a similar structure to humans in tendon physiology, there are marked differences, e.g., the tendon sheath configuration, the number of tendons, the number and type of the pulleys, the number of phalanges, and the vascular supply. Reports by Farkas et al. have described the anatomy of the chicken toe, but a standard anatomic nomenclature is still lacking .

Our goals in the present study were to review the anatomy of the flexor tendon system of the third (long) toe of the chicken, to expand knowledge of the vascular supply in these systems, and to examine the structures of the chicken flexor tendon system under light and electron microscopy in comparison with the human system.

Materials and Methods

Thirty feet from white Leghorn chickens were examined. In five the skin was removed from the plantar surface of the third (long) toe up to the metatarsal level. The tendon sheath was injected with methylene blue and mercurochrom solution at the level of the first IP. Joint. Using a Zeiss stereoscope, all the connective tissues overlying the sheath were removed and the location of the tendon sheath, as well as the number and position of the pulleys were examined. In five feet the tendon sheath was incised longitudinally over its full length and tendon locations, tendon insertions, and vincula were examined.

In five feet, the tendon-tendon sheet unit of the third (long) toe was removed and fixed in 10% formalin. The blocks were embedded in celloidin-paraffin, and serial sections were made. The slides were stained with HE, PAS-HE, Van-Gieson and Krutsay stain.

For scanning electron microscopy, blocks were made from the membranaceous part of the sheath at the level of the second phalanx, from the C3 pulley, and from the visceral tenosynovium at the same level in five digit samples. The blocks were fixed in 2,5% buffered glutaraldehyde and dehydrated. Then the specimens were dried with a critical-point drying method, coated with gold, and examined in an EM ASID 4 and a TESLA BS 300 electron microscope.

Results

The chicken's third (long) toe flexor tendons are covered by a tendon sheath extending from the insertion of the flexor profundus tendon just below the trifurcation of this tendon at the level of the distal tarso-metatarsus. It is an important difference between the chicken foot and the human flexor system that the tendon

sheath of the third (long) toe of the chicken is divided into two parts by a thin membrane at the level of the vinculum longum insertion.

The distal part of the tendon sheath forms a „cul de sac" at this level. The sheath - a thin, fragile, connective-tissue membrane - has thickenings called pulleys, similar to the structures present in the human hand. Recently Telepun et al. published a new description of the pulley system of the chicken's third (long) toe. We found that this toe of the chicken has five pulleys; namely one at the level of the metatarsophalangeal joint, one at the distal part of the distal part of the first, second, and third phalanges, and one above the third I.P. joint.

We propose to classify these structures as C1-5 from proximal to distal. Pulleys C1 and C4 are wide, about 5-7 mm in size and weaker then pulleys C2 and C3. Former contain fibers, both circular and cruciform orientations whereas pulleys C2 and C3 are narrow structures, 2 mm in size contain circular fibers. Pulley C5 is thin fragile structure containing circular fibers.

The flexor system of the chicken's third (long) toe is composed of three tendons , namely, the musculus flexor peforatus, the musculus flexor perforans and perforatus, and the musculus flexor profundus. This is a further considerable difference between the human and chicken flexor systems

Sections made from the tendon-tendon sheath unit at the portion between the third and fourth pulleys reveal the visceral and parietal parts of the tenosynovium. The parietal part has an external well-developed layer, rich in collagen fibers

Scanning electron micrographs of the chicken's parietal tenosynovium show an undulating wrinkled surface, especially at higher magnification the synovial cells may swell out from the surface and interconnected with fibrils and filopodia.

Discussion

The anatomic findings described concur generally with the descriptions published by Farkas et al. and Koch , however, more detailed and additional observations were made in our dissections.

The first of these differences is in the composition and classification of the tendon sheath. In contrast to Farkas et al. , the dorsal portion of the tendon sheath cannot be separated from the underlying periosteum and volar plates; it can be removed only together with associated structures. The sheath is firmly attached to the bifurcation of the flexor perforatus and superficialis tendon as well. The main difference is that the tendon sheath of the chicken's third (long) toe is divided into two parts by a thin membrane. The FDP is running in a separate sheath from the vinculum longum insertion. The importance of this finding is that the flexor tendon experiments are usually done in this region.

Regarding the pulley system, Farkas et al. , and similarly Telepun et al. described only two short pulleys on each of the phalangeas 1 and 2. We found the existence of five annular pulleys. Because of these new findings, we propose to classify these structures as C 1-5 from proximal to distal.

The construction of the chicken C1 and especially C4 pulleys shows a striking similarity to the human AP1 pulley in the tendon-tendon sheath anatomy. In addition no pure cruciform ligaments exist, although cruciform fibers can be observed. From a functional aspect, chickens exhibit three pulleys, C2, C3 and C4, while in humans the number of pulleys is two, an AP1 and an AD1 pulley . The difference in the number of pulleys can be correlated with the extra phalanx in the chicken digit.

We suggest the following nomenclature for tendons:

New	**Previous**
Flexor digiti superficialis vs. Proximalis - FDSP	Flexor digiti perforatus - FDP
Flexor digiti superficialis vs Distalis - FDSD	Flexor digiti perforans perforatus - FDPP
Flexor digiti profundus - FDP	No change

Our light- and electron-microscopic studies confirm the data reported by Inoue at al. and established the similarity of the histological structure of the tendon-tendon sheath unit between the human hand and the chicken foot. Since the chicken foot is a weight bearing structure and is designed to grasp and/or hold (in a modified primate fashion) and therefore a parallel between the human hand and the anatomic function of the chicken foot cannot be drawn.

4. Histology and Ultra structure of the Normal Tenosynovium and Pseudo Sheath in Chickens and Humans

In recent work the following questions were investigated using light microscopic, scanning electron microscopic, and transmission electron microscopic investigations:

1. What is the structure of the parietal and visceral layers of the normal tenosynovium and the pseudo sheath?
2. Where are the synovial cells and what is the morphology and function of these cells?
3. What is the mechanism of tendon healing within the pseudo sheath?

Materials

Young adult chickens were used as experimental animals because of the anatomic similarity between their digits and those of humans. Fresh human cadaver digits, amputated fingers, and little pieces of the tendon sheath of injured patients were studied. A total of 45 chickens and 18 human materials were used. Ten chickens and 6 humans served as controls. All the animals that suffered postoperative infection or an operative failure were excluded from the recent study. The experimental model was similar to human flexor tendon injuries, including scar formation and the two-stage reconstruction.

All chickens were anaesthetized with ketamine and local nerve block was given to the digital nerves using 1% Lidocaine. First the flexor digitorum profundus (FDP) tendon of the long toe of the chicken foot was injured at the level of the insertion of

the flexor digitorum superficialis (FDS). After 4 weeks the long toe was explored using a zigzag incision, and the scarred tissues were removed together with the remaining FDP stumps from the territory of the tendon sheath. A silicone rubber rod was implanted into the digit for replacement of the missing FDP tendon. A plaster cast was applied for two weeks. Six weeks after the silicon rubber implantation, the silicone rubber implant was replaced with a tendon graft taken from the other foot using only a small proximal and distal incision. A plaster cast fixation was applied immobilizing the metatarsophalangeal (MTP) and interphalangeal (IP) joints in flexed position for two weeks. Normal activity was allowed for the animals after the cast was removed. Specimens were obtained from the normal tendon sheath and from the pseudo sheath 6 weeks after the silicone implantation and 4 weeks after replacing the silicone implant by autogenous tendon graft. For light microscopy, paraffin sections were stained with haematoxylin-eosin and with Krutsay trichrome.
For scanning electron microscopy, samples were fixed in 2.5% glutaraldehyde at pH 7.4, were dehydrated in grading alcohol, and dried in a critical point dryer apparatus. The specimens were coated with gold and examined in a TESLA BS 300 scanning electron microscope. For transmission electron microscopy, tissue was fixed in 4% glutaraldehyde and 2% osmium tetroxide, embedded in Durcupan ACM and examined with a JEM 100 B type electron microscope.

Discussion

The structure of the synovial layer is controversial in the literature. Some authors did not find a continuous cellular lining of the normal synovial sheath or of the pseudosheath observing only an irregular tenosynovial layer . Others have observed a regular tenosynovial surface, using scanning and transmission electron microscopy . According to the scanning microscopic observations of the cellular protrusions of the lining cells of the vincula and the parietal sheath are covered with fibrils and vesicular particles, the synovial cells of the visceral surface are flat, enmeshed with filamentous fibrils. The structure described above has a similar built-up in both the normal and the pseudo sheath. The same regular architecture was found both in the chicken and human sheath.

The ultra structure and function of the synovial cells were studied first in the joint synovial membrane. Two types of synovial cells have been recognized by transmission electron microscopy. Type A cells have phagocytic capacity with features of absorptive macrophagic cells. Type B cells have the ultrastructural characteristics of secretory cells producing probably protein and hyaluronic acid.

The results of our experiment proved that the reorganization of the tendon graft takes place under this way undergoing a gradual reorganization . There is a possibility for intrinsic repair for the tendon graft under ideal conditions during the two stage procedure, according to the data from the literature and our experiments. The synovial fluid has probably important components to lubricate the newly formed sheath preventing adhesion formation. The neurovascular supply and the remodeling of collagen and early function are other important factors as well.

In some cases it is difficult to achieve the ideal healing conditions in clinical practice. Further investigations are necessary for the better understanding of the biological healing process altogether with its adaptation to the clinical practice. These efforts can result in the improvement of the final outcome after tendon reconstruction.

Conclusions

1. The normal visceral and parietal flexor tendon sheath contains regular layers of synovial cells. At 6 weeks the pseudo sheath has a similar appearance to the normal sheath.
2. The morphology and probably the function of type A and B synovial cells are also similar in the newly formed sheath.
3. Under ideal conditions the nutritional supply of the tendon graft is very important for the proliferation of the epitenon cells during the repairing process. According to our observation, the tendon graft undergoes gradual reorganization.

5. Problems of the two-phase flexor tendon reconstruction. Clinical experiences

The injuries of the flexor tendons are rather common. Initial treatment is essential in such cases, and they can determine the fate of the patient. In this regard it is especially sad that it is often impossible to give primer or delayed primary treatment due to the different reasons, such as the severe ness of the particular injury, other injuries, the danger of infections, or other reasons.

The literature shows the following methods used to try to prevent the scar formation around the tendon: 1., The use of artificial tendons 2., the use of blocking materials, that prevent scar formation between the tendon and its surrounding; 3., Use of pharmaceuticals to decreases the scar formation around the tendon 4., Development of a pseodosheath which provides a gliding surface to the transplanted tendon .

Material and method

93 patients well treated between January 1. 1980 and December 31. 1990 using two-phase tendon reconstruction at the Dept. of Traumatology University Medical School Pécs and the Dept. of Traumatology Markusovszky County Hospital.

The follow up examinations were done in March 1992, at which 53 patients showed up.

There were 44 men and 9 women. In 27 cases the right, while in 26 cases the left hand was involved.

Indications for the two-step tendon reconstruction were:

- Conquassating injury
- Previous unsuccessful surgery
- Extending scar formation of the tendon sheath
- Previous infection

Surgical technique

In most cases zigzag incisions were applied, recently we prefer to use middle-lateral incision based on biomechanical considerations . We are careful not to damage the intact parts of the tendon sheath. We take out all scary tissues while trying to carefully preserve the A2 and A4 pulleys. In case of extensive scaring the pulleys are replaced.

We have been using simple silicon rods with 4 or 5 mm diameters, since we do not have original silicon rods reinforced by Dacron. The silicon rod is securely fixed beneath the distal stump of the FDP. The proximal end of the silicone rod is placed beneath the proximal stump of the flexor tendon, but without any fixation. If only the fingers have scar formation we use short silicon rods, while in case of having extensive scarring on the palm as well, we use long ones, which reach the carpal region.

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Results

The follow up examinations of the of the patients was done using the Buck-Gramcko scheme. The results were excellent for 8, good for 20, acceptable for 14, and bad for 15 fingers, respectively. Our results are slightly worse than the ones given in the literature, due to the more than average bad results. At the same time about half

of our patients belonged to the bad preoperative prognosticated group, and that is higher than in the literature data.

Conclusion

Our conclusion is that the two-phase tendon transplantation is a promising and good, albeit not the only possible, method for most injuries involving flexor tendon injuries with bad prognoses. Those results that were achieved with animal experiments needs ideal conditions, usually cannot be reproduced in human injuries due to different biological and clinical factors. It is the experienced hand-surgeon, who can determine based on the preoperative examinations what the best surgical procedure should be.

6. New results

The results of the experimental investigations of flexor tendon reconstruction and the clinical experiences can be summarised as follows:

1. Investigations of the experimental model:

1. That new fact has a paramount importance, the chicken third (long) toe has a devided tenosynovial sheath. We have to take into account during the experimetal planning this fact, the FDP (flexor digitorum profundus) is running in a separate tendon sheath from the insertion of the vinculum longum.
2. The exact description of the pulleys of the third (long) toe of the chicken, and introduction of a new terminology.
3. The description of the vincular system of the third (long) toe of the chicken feet. It was established the FDSD (flexor digitorum superficialis distalis) has a separate vincula.
4. The exact circulation of the third (long) toe of the chicken was described, and the presence of the digitopalmar arch was verified as well.

5. It was pointed out, the light-, and electron microscopical structure of the third (long) toe of the chicken toe has a very similar structure to the human tendon-tendon sheath unit.

2. Comparison of the ultra structure of the normal tenosynovium and the pseudo sheath.

1. Type A (phagocytic capacity) and type B (secretory capacity) synovial cells were demonstrated in the chicken as an experimental model, in the pseudo sheath in chicken and in the human tenosynovium.
2. It was proved experimentally, the incorporation of the tendon transplant built in with an intrinsic mechanism.
3. The role and importance of the synovia was emphasized during the tendon healing.

5.3. Clinical experiences during two phase tendon reconstruction.

1. Ideal circumstances were provided according to the experimental data during the clinical practice.
2. The choose the most appropriate surgical method according to the preoperative prognosis.
3. The results were evaluated compared to the preoperative prognosis.

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