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Flexor Tendon Repair in the Digital Sheath of the Hand

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Summary. **The author has attempted to review the most significant contributions to the development and current status of flexor tendon repair in the digital sheath. Experimental reports revealed that the flexor tendon could heal by itself and that both the intratendinous blood circulation and the synovial diffusion were important for core union and superficial union respectively.**

Although controversy still persists regarding the different repair techniques, the management of the sheath and the method of postoperative mobilization, flexor tendon repair in the digital sheath has been recognized as one of the most delicate but effective procedures modern hand surgery has achieved. It requires thorough understanding of the normal anatomy and physiology of the flexor tendon and of the pathophysiology following injury, and also technical skill, and well-planned postoperative therapy involving the surgeon, the therapist and the patient himself.

The successful restoration of function of the flexor tendons severed in the digital sheath has been one of the most difficult problems in the hand surgery. In the early era of modern hand surgery, Bunnell[1] attempted primary repair of the flexor tendon in the digital sheath with immediate success but eventual failure due to the ensuing scar formation and firm adhesion to surrounding tissue. Later, Hauge (1955),[2] Kelly (1959)[3] and Lindsay (1960)[4] reported unsatisfactory results of primary repair. Faced with consistently unsatisfactory results, the term "no-man's land" was coined, meaning that the flexor tendon should not be touched in the proximal half of the digital sheath between its inlet and the flexor digitorum superificialis insertion, the region later described as Zone 2 by Verdan.[5] Difficulty in treating the severed flexor tendon in this region was ascribed to the characteristic anatomical structures of the digital sheath,[6] that is, the fibro-osseous canal in which the flexor digitorum profundus penetrates the flexor digitorum superficialis, and insufficient understanding of physiological characteristics of the flexor tendon-muscle unit. The tremendous investigative efforts in the areas of flexor tendon anatomy, biomechanics, nutrition and healing have provided a clue to improving the results of repair of the flexor tendon.

This article reviews the most significant contributions to flexor tendon repair and describes current repair technique and postoperative management.

Historical vicissitudes of the methods of treatment for flexor tendon injury

Based on the experience that the repaired flexor tendon became eventually embedded in the scar tissue in the digital sheath, Bunnell[1,7,8] proposed two-stage tendon repair consisting of primary repair and secondary tenolysis to be done in 6 weeks. He emphasized the importance of "atraumatic technique" from the standpoint of prevention of postoperative adhesion and devised a technique of tendon repair, "end-to-end suture at a distance", in which the tendon stumps were approximated as in the end-to-end type with fine sutures by eliminating the muscle pull with a pull-out wire placed through the proximal tendon at the level apart from the tendon juncture. This idea led to development of the "transfixation technique" proposed by Salomon,[9] Montant[10] and Bove[11] in which the proximal stump was pulled distally and transfixed with a safety pin or straight needle to overcome the muscle pull. Bunnell devised a free tendon graft

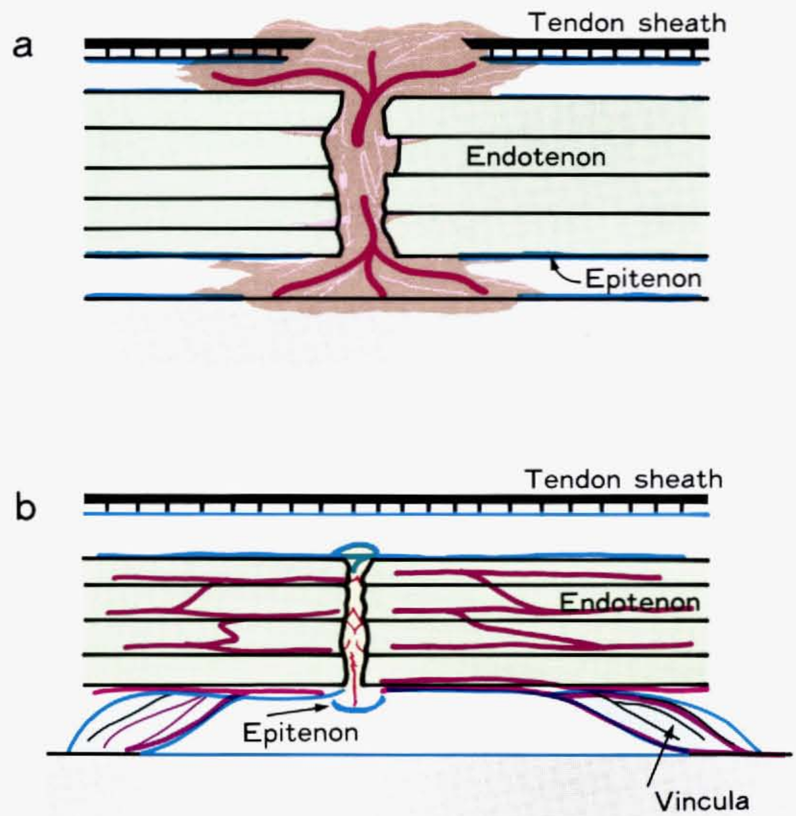

Fig. 1. Two concepts of tendon healing. **a.** Healing with connective tissue originating from the surrounding structures. **b.** Healing with the tendon's own tissue such as epitenon and endotenon.

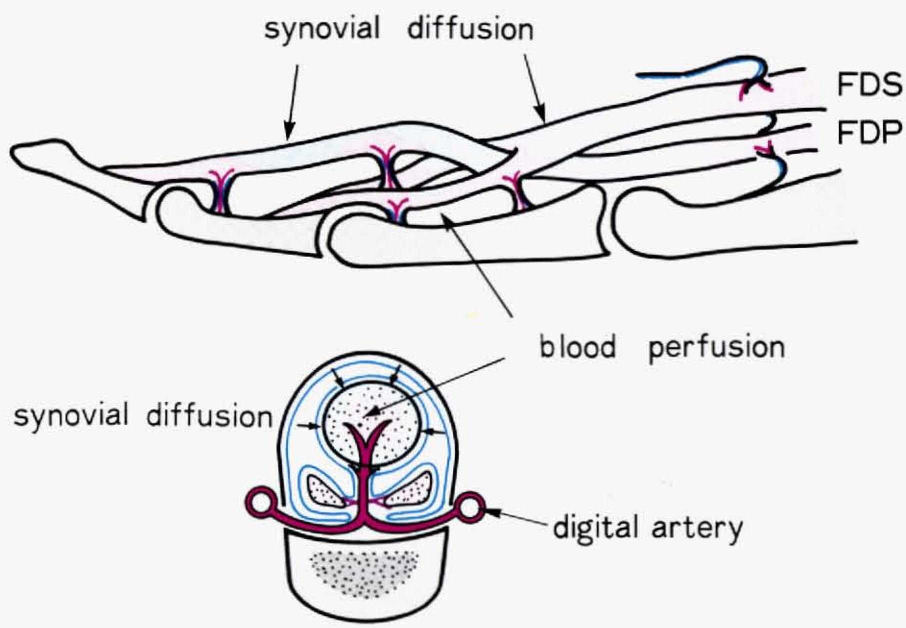

Fig. 2. Nutrient pathways of the flexor tendons. The red areas are those in which blood perfusion is relatively important.

replacing the whole length of the injured flexor lying in the sheath in longstanding cases to avoid suturing the tendon in the sheath.[12] Since Boyes (1950)[13] and Pulvertaft (1956)[14] had reported good results of free tendon graft, it had been believed to be the only way to treat the flexor severed in the no-man's land until Verdan[15] reported a satisfactory result of primary repair using a pair of transfixation pins in 1960. Although 29% of his cases needed secondary tenolysis or free tendon graft because of adhesion, his report became a turning point in re-evaluating the primary repair. In 1967, Kleinert[16] reported that 87% of primary repairs in the no-man's land performed in the period of 10 years were excellent or good. His method was characterized by fine anatomical repair and early mobilization of the injured digit using rubber band traction.[17,18]

Through such historical vicissitudes, it became accepted that primary repair would achieve better results than traditional free tendon graft in treatment of flexor tendon laceration in the digital sheath.

Healing of the tendon

Regarding the healing potential of the tendon, there were two controversial concepts. One is the concept advocated by Adams,[19] Skoog[20] and Potenza.[21-23] They insisted that such a tendon as the finger flexor covered with the synovial sheath did not have healing potential in its own tissue. They thought that the connective tissue originating from the surrounding structures such as the digital sheath or gliding floor came into the injured site of the tendon and repaired it (Fig. 1a). The other concept is the one advocated by Garlock,[24] Lindsay[25] and others. They claimed that the tendon's own tissues such as epitenon and endotenon could repair the severed tendon (Fig. 1b). Mason,[26] and later Flynn,[27] believed that both processes were important.

In 1974, Matthews[28] and Tokita[29] independently proved that the severed flexor tendon of the chicken would heal by itself without adhering to the surrounding tissue in the experimental model in which the integrity of the sheath and vincula was maintained. At that time several reports of intrinsic vascularization of flexor tendons were published.[30-34] Since then it has been emphasized that blood circulation to and in the tendon was very important for tendon healing. The vincula system was recognized as the important route of blood supply to the tendons in the sheath. New suture methods which do not compromise the intratendinous circulation were then developed one after another.

In 1977, McDowell[35] and Lundborg[36] pointed out that the tendon could heal by synovial diffusion in the sheath. Lundborg[37] showed in 1978 that the suture site in a short piece of the tendon placed in the knee joint healed in an experiment of the dog to prove that the superficial layer of the tendon heals with synovial diffusion. In 1982, Manske[38] showed in an experiment with a monkey that the uptake of tritiated proline through synovial diffusion was much greater in all areas of the flexor tendon, except for the distal segment, than the uptake through blood perfusion. He also showed that the uptake through synovial diffusion was relatively less in the areas supplied with blood perfusion through short or long vinculum (Fig. 2). In 1981, Katsumi[39] showed in an experiment of the monkey that a piece of tendon placed in the knee joint healed (Fig. 3) but that the healing of repaired tendon wrapped with dialysis membrane and placed in the knee joint was delayed by immobilizing the joint. This delay of the tendon healing in an immobilized knee joint was attributed to insufficient synovial diffusion by lack of pumping effect of the joint motion. It was also proved that a piece of repaired tendon wrapped with dialysis membrane and placed in the subcutaneous tissue of the abdominal wall healed by diffusion of tissue fluid. Those facts suggest that both intratendinous blood circulation and synovial diffusion are essential for solid intrinsic union of the severed tendon. The former takes a part in union of the tendon core and so does the latter in that of its superficial layer.

Management of the flexor digitorum superficialis

Since primary repair of the flexor tendon in the flexor sheath was recognized by Verdan,[15] it had been thought to be wise to excise the lacerated flexor digitorum superficialis and to repair the profundus alone to obtain wider room for better gliding. Kleinert[17,18] demonstrated that better results were obtained when both tendons were repaired.

The long vinculum of the profundus arises at the level just proximal to Camper's chiasm of the superficialis and has connection with the short vinculum of the latter tendon (Fig. 4). Excision of the superficialis may cut the blood supply to the profundus through those vincula and also leaves cut surfaces of tendon slips uncovered beneath the repaired profundus tendon. Repair of both tendons has the advantage of preserving the vincular blood supply to the profundus tendon, providing a smooth gliding bed for the profundus tendon and eventually restoring independent finger motion and strong grip.

Fig. 3.

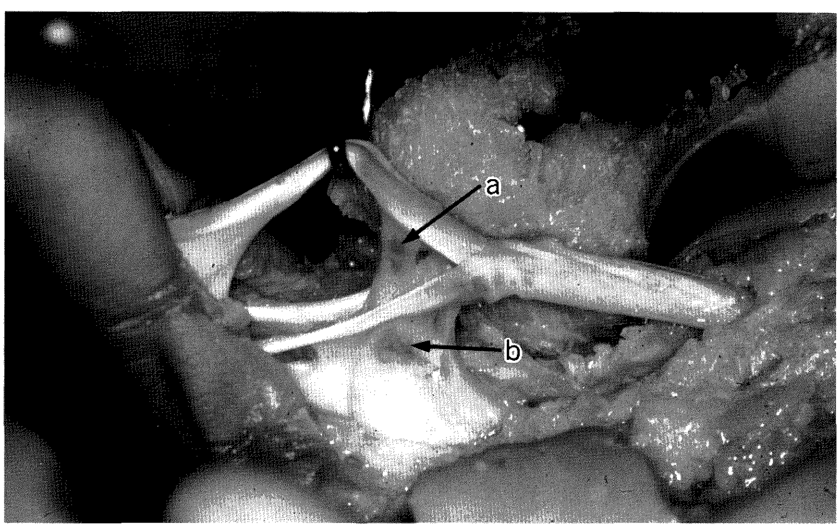

Fig. 4.

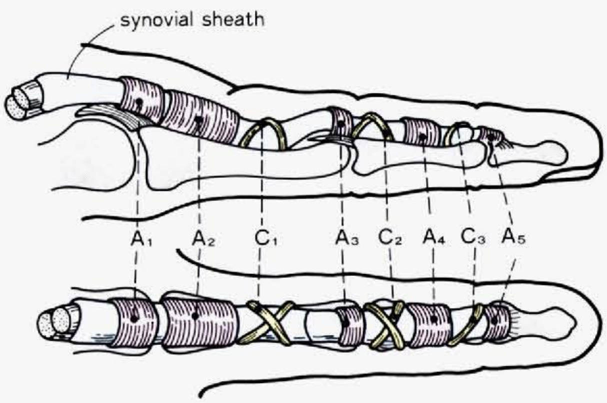

Fig. 5. Anatomy of the digital flexor sheath. A_{1-5}: annular pulley, C_{1-3}: cruciform pulley. A_5 pulley was described by Idler, R. S. (Redrawn from Doyle, J. R.: In A. A. O. S. Symposium on Tendon Surgery in the Hand. C. V. Mosby, Saint Louis, p. 81-87, 1975.)

Management of the digital sheath

Doyle[40] reported the macroscopic and functional anatomy of the flexor tendon sheath in 1974 (Fig. 5). He proved that preservation of both A2 and A4 pulleys was essential for full flexion of a finger. Based on this study, most hand surgeons would repair the flexor tendon preserving only A2 and A4 pulleys and leaving other areas of the sheath open.

Considering the above-mentioned nutritional aspect, it is imperative to restore the entire sheath in which the synovial fluid circulates on finger motion. Restoration of the entire sheath also produces another biomechanical advantage pointed out by Lister.[41] When a window made in the sheath for repair of the flexor tendon is left open, even a slight step at the suture site of the tendon catches the edge of the window and pushes the remaining part of the annular pulley. This mechanism decreases the inner diameter of the digital sheath and hinders the tendon from passing this area. Complete closure restores the intrathecal circulation of synovial fluid and prevents the suture site of the tendon from impinging on the window edge.

Eiken[42] reported that sheath repair favourably influenced the recovery of tendon excursion but most reports have been inconclusive. A comparative prospective study of the surgical management of the tendon sheath after repair of flexor tendons in zone 2 by Saldana[43] revealed no statistical difference between the results of open sheath and closed sheath. Manske[44] pointed out that a "water-tight" closure of the sheath may narrow its diameter and restrict the gliding of a swollen tendon and stated that the sheath should be reconstructed with retinacular, fascial or synthetic grafts.

Repair of digital vessels and nerves

When the neurovascular bundle has been cut as well, the digital nerve should be repaired under magnification. It has not been conclusive if repair of the digital artery gives better results. Although Kleinert stated the artery should be repaired, the author's (Saito, 1984) analysis[45] revealed that repair of the artery in the cases with laceration of the unilateral or bilateral digital arteries did not give better results than in a non-repair group. Repair of the artery, however, seemed to be beneficial in the repair group because the circulation was considered to be so poor as to compromise the tendon healing, leading to worse results. Therefore, this result does not justify leaving the digital arteries unrepaired. It is theoretically recommended to repair the digital artery in order to restore the blood supply to the profundus tendon through the vincular artery arising from the transverse branch of the proper digital artery.

Suture materials

Since Bunnell[8] and Pulvertaft[46] proposed suturing tendons with stainless steel wire which produced little tissue reaction, it was used for years. With development of the chemical industry, many new suture materials of chemical synthetics have been produced for the last two decades. Srugi[47] compared, histopathologically, the tissue reaction of ten kinds of suture materials placed within the flexor tendons of mongrel dogs (Fig. 6). Monofilament nylon produced the least reaction. Dexon® (polyglycolic suture) showed a similar

Fig. 3. Process of the healing of a piece of the flexor digitorum profundus tendon wrapped with a dialysis membrane and placed in the knee joint (by courtesy of Dr. M. Katsumi)
a, b and c show macroscopic and microscopic findings seen 2, 3 and 4 weeks respectively, after the operation.

Fig. 4. Vincula of the flexor tendons. The blood supply to the profundus through its long vinculum (a) depends on the integrity of the chiasm and short vinculum (b) of the superficialis.

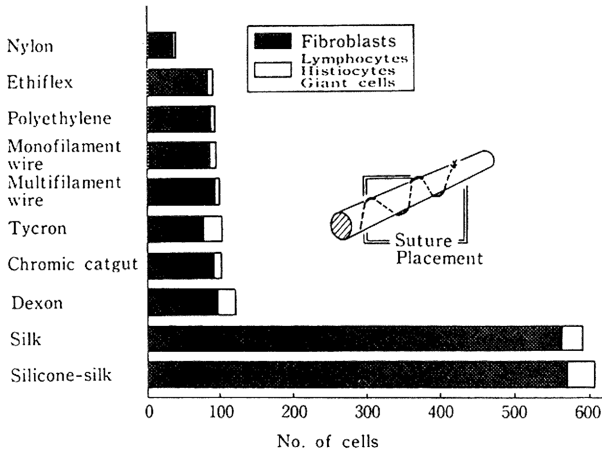

Fig. 6. Cellular response to various suture materials seen 4 weeks after their placement through the flexor tendons of dogs (Redrawn from Srugi, S. et al.: Plast. Reconstr. Surg., 50: 31-35, 1972.)

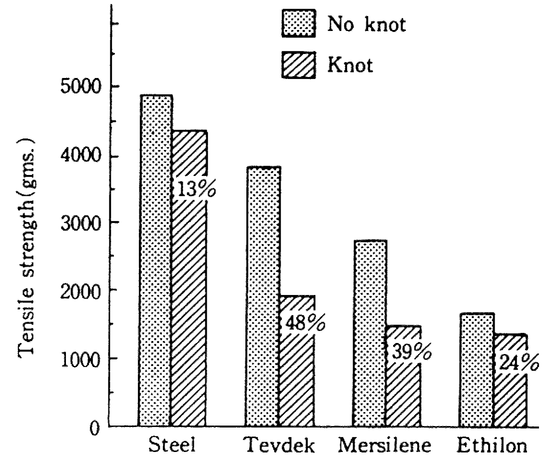

Fig. 7. Tensile strength of two strands of the 4-0 material tested (Redrawn from Urbaniak, J. R. et al.: In A. A. O. S. Symposium on Tendon Surgery in the Hand. C. V. Mosby, Saint Louis, p. 70-80, 1975.)

degree of reaction in the area immediately adjacent to the periphery of the suture but a greater reaction within the interstices of the braided fibrils. Tissue reaction to Ethiflex® (polyester fiber treated with Teflon), monofilament stainless steel wire and Tycron® (Dacron polyester fiber treated with silicone) was 2-2.5 times greater than that of nylon. Silk and silicone-treated silk produced the most intense reaction, approximately 14 times greater than nylon. From this study one may conclude that the best suture material for flexor tendons of the dog is nylon and that the least favorable sutures are silk and silicone-treated silk. Other factors such as tensile strength, knot slippage, tissue trauma and ease of handling, however, should be considered when those materials are used for tendon suture.

Urbaniak[48] tested the tensile strength of four suture materials of 4-0 size before and after a square knot was made in a strand (Fig. 7). Of the three kinds of synthetic materials, Tevdek® (Teflon impregnated braided polyester fiber) was the strongest with Mersilene® (braided polyester fiber) being the second and Ethilon® (nylon) the third in tensile strength. Tying a knot in the strand markedly altered its tensile strength. Ethilon showed only 24% reduction in tensile strength while Mersilene and Tevdek showed 39% and 48% reduction, respectively. However, none of the synthetic materials was as strong as stainless steel wire, which was also least affected by knotting with only 13% reduction in the original tensile strength. Ketchum[49] evaluated various kinds of suture materials used for repair of flexor tendons of the dog, revealing that monofilament stainless steel wire was initially the strongest but that this strength decreased by 50% after three weeks. Mangus[50] also showed that monofilament stainless steel is too inelastic and brittle to serve well and long as a buried suture. The surface of wire is also very vulnerable to damage even with gentle rubbing, producing flaking with toothlike excrescence of the metal which contributes to a sawing effect.

Methods of tendon suture

The techniques for tendon suture have varied considerably since the description by Bunnell of the buried criss-cross suture and the removable pull-out suture (Fig. 8).

The tensile strength of various types of tendon sutures was studied by Urbaniak, Ketchum and others. Urbaniak[48] showed the superiority of Kessler's suture[51] to Bunnell's buried criss-cross suture in the early phase of tendon healing (Fig. 8a, d), in that the latter type of suture compromises the intratendinous circulation. Tajima[52] devised the method using double horizontal mattress sutures to minimize disturbance of the intratendinous circulation (Fig. 8c). The tensile strength of this type of suture during the period of healing was compared with that of Bunnell's criss-cross, Kessler's and double right angle sutures. Initially, it was nearly one half as strong as that of Bunnell's but increased suddenly after the seventh day to three times its initial strength. Bunnell's suture which seems to compromise the intratendinous circu-

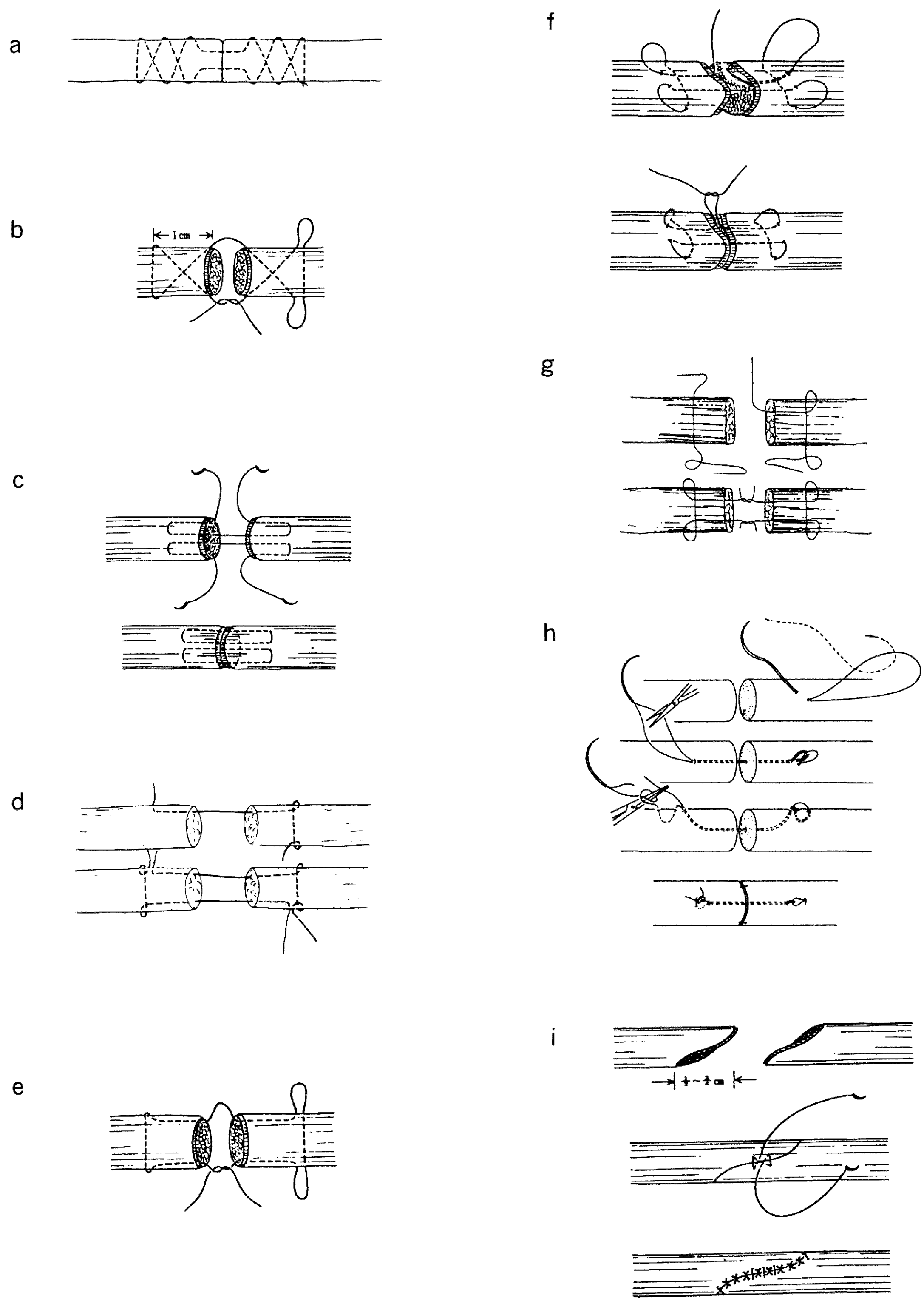

Fig. 8. Various types of tendon suture. **a.** Bunnell's buried criss-cross suture. **b.** Kleinert's criss-cross suture. **c.** Tajima's double horizontal mattress suture. **d.** Kessler's grasping suture. **e.** dumbbell suture. **f.** Pennington's locking loop suture. **g.** Tajima's rectangular parallel suture. **h.** modified Tsuge's intratendinous suture. **i.** Becker's bevel suture.

lation was the strongest initially but lost its tensile strength markedly after the fifth day and did not restore its initial strength by three weeks. Microangiograpy performed just after tendon repair revealed that double horizontal mattress sutures least affected the intratendinous circulation. The intratendinous tendon suture devised by Tsuge,[53,54] was also found to not compromise the circulation in the tendon much and to become four times as strong as the initial strength (Fig. 8h). Wade,[55] evaluating the mechanical limitations of the modified Kessler's suture (Fig. 8e, f, g), found that the peripheral running stitch was an important component of the suture not only to tuck the margin of the stump in but to prevent gap formation. Lister[56] emphasized the inverting of the margin of the stump by placing a Lembert-type suture through the epitenon to diminish the tendon bulk at the suture site.

Now that early mobilization excercise has been accepted as an important part of treatment for flexor tendon injury, it is essential to select a suture method which does not compromise the intratendinous circulation much but also is strong enough to withstand stress produced in early motion exercise. Figure 9 shows the relationship of various types of tendon sutures to the intratendinous circulation, which is important for core union of the tendon, and to the tensile strength, which is important for early mobilization. Two factors, blood circulation in the tendon and tensile strength, are usually incompatible with each other. Because there is no suture to fulfill those two requirements completely at present, one of the modified Kessler-type sutures or Tsuge's intratendinous suture is the most appropriate choice. Among modified Kessler-type sutures, Pennington's locking loop suture[57] seems to have the high resistance to gap formation (Fig. 8f). In this suture, the longitudinal stitch placed from the cut surface is pulled out anteriorly and then the transverse stitch is placed superficial to the former so that a small bundle of tendon fibers is locked with a loop of suture at the corner. Tajima[58] modified Kessler's suture in such a way as a suture with a needle at each end is placed through each stump in a rectangular fashion so that each needle comes out into the cut surface and then each thread of one suture is tied with a corresponding thread of the other suture within the juncture (Fig. 8g). This method is particularly convenient because the suture can be placed in a tendon end as soon as it is identified and the protruding threads may then be used to pass the tendon through the flexor sheath without damaging the tendon further by handling it with instruments. Becker's bevel suture[59,60] is strong enough to withstand the stress produced on active motion exercise without splinting and does not seem to compromise the intratendinous circulation much (Fig. 8i). Shortening of the tendon by beveling each stump of the transected tendon, however, is a serious drawback.

Early mobilization excercise

The efficacy of early mobilization on prevention of adhesion of the repaired tendon was pointed out by Lexer (1912)[61] and Bunnell (1918)[1] but it had not been put to practical use because of the fear of rupture of the tendon at suture site and of the possibility of increasing tissue reaction and the ensuing thicker adhesion.[62] The technique of early mobilization supported with rubber band traction was reported by Young[63] in 1960, prior to Kleinert's report. At that time, Potenza[22] claimed that the flexor profundus tendon within the digital sheath did not have healing potential and that adhesion of the tendon with surrounding tissue was essential in its healing process and inevitable, based on the results obtained in experiments using dogs. If it were a fact that the flexor tendon within the sheath does not have healing potential, early mobilization of the repaired tendon would delay its healing.

As proved by Matthews,[28] an isolated cut in the tendon can heal by itself in a situation in which the surrounding tissue is kept intact. Practically, we do not meet this situation. The surrounding tissue, such as the tendon sheath, subcutaneous fat and skin, is cut as well. In this situation the wound heals in one scar with those structures adhering to each other as described in the "one wound-one scar" concept advocated by Peacock.[64] Only early motion could prevent the repaired tendon from adhering to the sheath or gliding floor.

There are basically two types of early motion exercise reported. One is the active extension and rubber band flexion method advocated by Kleinert[17,18] and Lister.[56] The other is the controlled passive motion method advocated by Duran,[65] which consists of passive motion of DIP and PIP joints with the MP joint and wrist being kept in moderate flexion.

In electromyographic study, Lister[56] proved that the flexor profundus showed very little and low discharge in extending fingers actively. According to this study, there is less tension produced at the junction of the flexor tendon in extending fingers actively rather than passively.

McGrouther[66] attempted to analyse the amount of tendon motion which would occur in the original

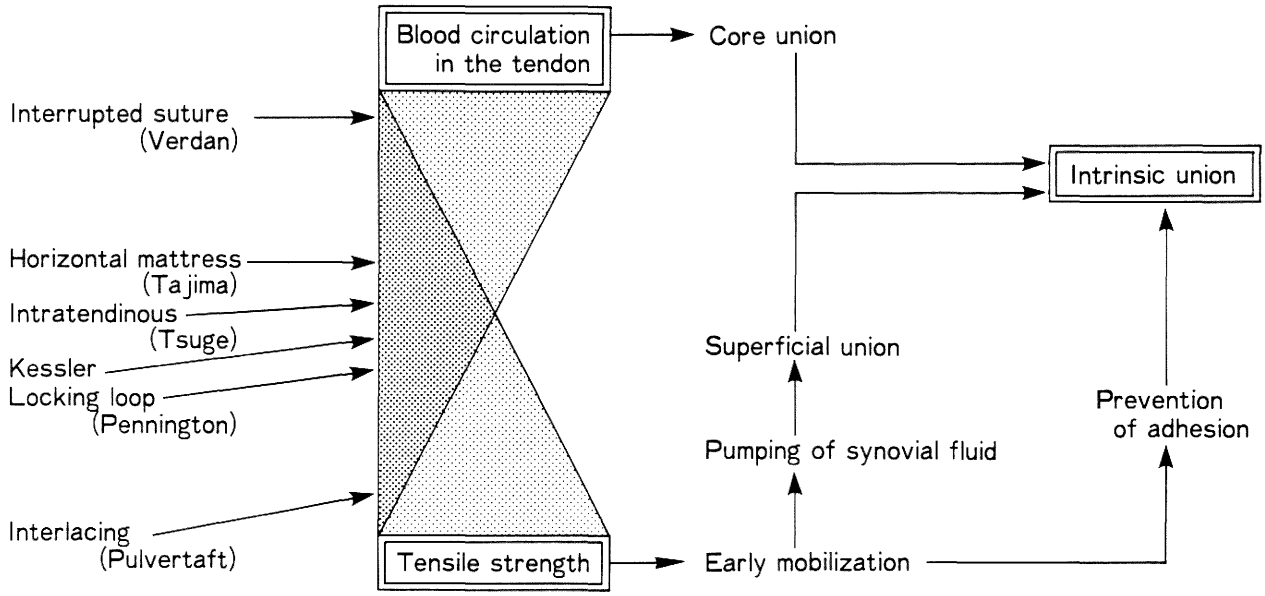

Fig. 9. The tensile strength and the effect on the intratendinous circulation of various types of tendon suture in relation to tendon healing and early mobilization

Kleinert's splinting and found this splinting to produce ranges of joint motion of 33° at the DIP joint and 74° at the PIP joint in normal subjects. He then calculated that the excursion of profundus tendon occurring at the level of proximal digital segment was 3.2 mm relative to the superficialis tendon and 9.6 mm relative to the sheath. He concluded that this splinting was a poor mobiliser of the DIP joint and that cross-union between the profundus and superficialis tendons could occur.

For the last few years, there have been a number of papers on modification of Kleinert's method[67–70] published. Those splints were designed to create more complete flexion and extension of the DIP joint, either by placing a pulley in the distal palm under which the rubber band passes or by increasing the amplitude of the rubber band with the addition of a spring. Strickland[71] popularised the controlled passive motion exercise using an extension-blocking splint, slightly modified from that described by Duran.[65] He showed that the results obtained in the groups undergoing controlled passive motion were definitely better than those in the immobilization group. Bunker[72] used the Toronto Mobilimb Continuous Passive Motion machine for postoperative mobilization, obtaining results of excellent or good in 82% of flexor tendon lacerations in zone 2. Chow[73,74] combined controlled active extension and passive flexion imparted by rubber band, and controlled passive extension and flexion exercise.

Functional results

After Kleinert reported in 1967 that 87% primary repairs in "non-man's land" were excellent or good, there appeared quite a number of reports on the results of primary repair in zone 2 followed by either active extension exercise or passive motion exercise. Their results, however, were not so good as Kleinert's. Earley (1982)[75] reported that 55.5% of primary repair in zone 2 treated with almost the same regimen as Kleinert's were graded excellent to good. The author (Saito, 1983)[76] reported that the overall results of 41 digits were 53.7% excellent to good, but 23 digits treated by senior staffs were graded 73.9% excellent to good. Results of the looped nylon intratendinous suture of Tsuge were reported by Ikuta[77] in 1985, showing 68.3% graded excellent to good. Strickland (1987)[78] found that 68% of combined repairs of the flexor profundos and superficialis with postoperative passive motion exercise were excellent or good and that digits with sheath repair recovered better than those without repair (77% excellent or good versus 56% excellent or good, but without statistical significance).

More recently, improved results have been reported. Chow (1987)[73] reported the results of flexor repair with a postoperative regimen of combined active extension and passive extension-flexion exercise. 82% of 44 digits with complete division of both tendons in zone 2 were rated excellent, 16% good and 2% fair according to Strickland's criteria. Werntz (1989)[70] reported the results of patients of Kleinert's groups treated with a new dynamic splint utilizing a spring-loaded roller bar in the distal palm and a coiled lever in the distal forearm. 76.1% of 46 fingers with zone 2 flexor injury had excellent results and 23.9% good results according to Strickland's modified criteria. No cases were rated either fair or poor.

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