Tendon transfers as applied to tetraplegia

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Although not many basic surgical procedures exist for patients with tetraplegia, there are many variations and several combinations among them. Because this article focuses primarily on the technical aspects of surgery, the authors describe their current experience and personal choices, both of which were deeply influenced by Professor Eduardo Zancolli’s ideas.

Principles

The general principles of tendon transfers (eg, joint mobility, motor force) apply to tetraplegia; however, some specific technical points should be emphasized:

- Spasticity leads to unpredictable results if surgery is attempted.
- The goal is to restore elbow extension, then the opening and closing of the hand.
- Conflicting positions of postoperative immobilization explain why two surgical stages usually are required for the hand: (1) an extensor phase to restore or reinforce finger and thumb extension and to stabilize the thumb, and (2) a flexor phase to restore finger and thumb flexion. If the flexor phase was performed before the extensor phase, the hand is at risk for remaining permanently closed.
- A single longitudinal incision on the radial aspect of the forearm from the elbow to the wrist allows both the harvesting of the donor muscles (brachioradialis [BR] and extensor carpi radialis longus [ECRL]) and the transfer to either the dorsal or the volar paralyzed recipient muscles. Thus, the same incision is used for the extensor and flexor phases and can be used for carpometacarpal arthrodesis if needed.
- When active extrinsic metacarpophalangeal (MP) extension and interphalangeal (IP) flexion of the fingers are both restored, an intrinsic minus-claw deformity is likely to occur and should be prevented.
- Although not specific to tetraplegia, the transferred tendon is passed through three or four small slits in the recipient tendon, is looped back, and is sutured to itself under proper tension.
- A 4-week postoperative immobilization is required to allow tendon healing. Afterward, the goals of rehabilitation are (1) to recover the preoperative range of motion of immobilized joints, and (2) to train the transferred muscles in their new functions by active contractions and intensive occupational therapy. Performing these in a specialized rehabilitation center with an experienced team of physiatrists, physiotherapists, and occupational therapists is of paramount importance [1,2].
Active tendon transfers

Generally, there are four main potential donor muscles in tetraplegic patients: the biceps and deltoid for the elbow and the BR and ECRL for the wrist and hand.

Elbow extension

When elbow extension is paralyzed, it must be restored before the hand. Two procedures are available: the deltoid-to-triceps transfer and the biceps-to-triceps transfer. To avoid the risk of shoulder destabilization, the authors use the former when the upper part of the pectoralis major is active; otherwise, they use the latter. In both cases, passive elbow extension must be complete (or nearly complete) before surgery.

Biceps

The first biceps-to-triceps transfer seems to have been performed in 1951 by Leo Mayer in a tetraplegic patient 16 years of age [3]. Later, Friedenberg [3] performed this procedure in one poliomyelitis case. In his description, the biceps muscle was passed subcutaneously around the lateral border of the arm. Zancolli [4,5] also advocated this transfer in tetraplegia, rerouting the biceps laterally and fixing its tendon in the olecranon.

Generally, the biceps-to-triceps transfer has a poor reputation compared with that of the deltoid-to-triceps transfer advocated by Moberg in restoring elbow extension [6,7]. The main criticisms were that it is not a reliable procedure, that the strength of elbow flexion is weakened, and that there is a risk of radial nerve injury when the biceps is routed around the lateral border of the arm [5].

To avoid the risk of radial nerve injury, the authors use the medial route [8,9], as advocated by Kutz et al. [10] and Allieu et al. [11]. In the authors’ 29-case experience, the outcomes have showed that the technique is effective and reliable. No complications were encountered and, obviously, no radial nerve injury was observed owing to the medial routing of the biceps. Similarly, although the tension of the transfer was set to the maximum, the authors did not observe clinical evidence of median nerve or vascular compression.

The major potential drawback was a 47% reduction in elbow-flexion power after the biceps transfer [9]. This figure is much higher than the 24% reduction noted with the lateral route [5,12]. As in the Zancolli [5] series of 13 patients, however, none of our patients complained about this decrease, which primarily involves the final degrees of the flexion range [13]. Moreover, all of the authors’ patients who could benefit from the same procedure on the opposite arm requested it and were satisfied. The authors, therefore, advocate the biceps-to-triceps transfer through a medial route instead through the lateral route.

Technique. After preparing and draping the arm and the shoulder, a sterile Esmarch bandage is applied to the arm as proximally as possible [9]. A bayonet-shaped incision is made vertically along the medial aspect of the arm, horizontally at the anterior crease of the elbow, and then vertically along the proximal forearm over the BR belly (Fig. 1A). The skin margins are elevated along with the underlying deep fascia, and care is taken to preserve the cephalic and basilic veins and the lateral cutaneous nerve of the forearm. The bicipital aponeurosis is divided, and the tendon of the biceps is dissected to its insertion into the radius, where it is transected as distally as possible (Fig. 1C). Avoiding any damage to the recurrent radial vessels at this point is of utmost importance because they are the main blood supply of the BR and the extensor carpi radialis muscles [14], which will be transferred in a second stage.

The muscle belly of the biceps is dissected proximally and raised up to its vascular pedicle, which always enters the deep aspect of the muscle at its proximal third. Some minor distal vessels frequently are encountered and can be ligated.

A posterior separate curved incision is made on the dorsal aspect of the distal third of the arm (Fig. 1B). The tendon of the triceps is exposed in its entire length, and a wide tunnel is made under the deep fascia of the medial aspect of the arm, leading from the posterior to the anterior wound. The proximal border of this tunnel is located near the distal end of the Esmarch bandage (Fig. 1D). Once the skin flap has been elevated, the deep fascia is excised entirely to prevent its adhesion to the transferred tendon.

The Esmarch bandage is then removed, allowing the incision on the medial aspect of the arm to be lengthened proximally to improve the dissection of the proximal part of the biceps (Fig. 1E). At this stage, making certain that the biceps is freed entirely in a straight line between its vascular pedicle and the new distal reinsertion of its tendon is useful. Similarly, the subcutaneous tunnel at the medial aspect of the arm should be made large enough (Fig. 1F) for the passage of the transfer.

The tendon of the biceps is then interwoven into the tendon of the triceps and secured with
Fig. 1. Biceps-to-triceps transfer. (A, B) Skin incisions. (C) The distal tendon of biceps is near the end of the retractor surrounded by recurrent radial vessels. The musculocutaneous nerve is located along the tendon. The superficial veins are left intact. (D) A wide tunnel is made at the medial aspect of the arm under the deep fascia, which is excised. (E) The biceps is dissected up to its main vascular pedicle, then dissection is pursued after removal of the Esmach bandage. (F) The biceps is passed through the tunnel at the medial aspect of the arm. (G) The biceps tendon is interwoven and strongly sutured to the triceps tendon under maximum tension. The shoulder is on the left, the forearm on the right. (From Revol M, Briand E, Servant JM. Biceps-to-triceps transfer in tetraplegia. The medial route. J Hand Surg [Br] 1999;24:235–7; with permission.)
multiple 2-0 nonabsorbable sutures (Fig. 1G). The tension of the transfer is set to the maximum while the elbow is held in full extension so that the elbow cannot be flexed passively beyond 30° when the arm is abducted approximately 30° to 40°. In some cases, the tendon of the biceps can be lengthened proximally by up to 3 cm at its musculotendinous junction by carefully stripping away the insertions of the distal muscular fibers of the biceps from the tendon [15].

Finally, hemostasis is secured, two suction drains are placed, and the skin is sutured. A well-padded, long-arm, fiberglass splint is applied to hold the elbow in 10° of flexion and the wrist in 30° of extension. The forearm is more comfortable in pronation than in supination. The shoulder is left free.

Postoperative management. Immobilization is continued for 4 weeks. An active exercise program is begun to gain flexion of the elbow at a rate of 15° to 20° per week. Intensive occupational therapy is used to train the biceps to extend the elbow.

Deltoid

Transfer of the posterior deltoid seems to have been first published by Merle d’Aubigné for brachial plexus lesions [16]. Möberg was the first author who applied it to tetraplegia [6] and subsequently was followed by many others [17–21]. Because there is a 10- to 15-cm gap between the deltoid and the triceps distal tendons, an interposition is required. Many technical variations have been described using interposition materials, such as tendon grafts, fascia lata, and prosthetic devices. The following section describes the authors’ present technique, which was derived from Allieu’s and Teissier’s procedures. The authors’ contribution is to wrap the triceps around the interposition material.

Technique. The patient lies supine with the operated upper limb on a hand table. The surgeon is located proximally, with two assistants standing across the hand table. Obviously, no tourniquet use is possible, so the amount of bleeding varies from case to case, especially in the area of the del-
toid tendon. The first part of the procedure is performed with the patient’s forearm lying on his trunk and his or her arm in adduction. The skin is incised in a lazy S that extends from the anterior part of shoulder to the olecranon (Fig. 2A). Skin flaps are elevated with the fascia, and the superficial aspect of the triceps muscular belly and distal tendon are exposed and dissected away from the surrounding fascia and peritenon. The superficial aspect of the deltoid is exposed similarly, from the anterior to posterior border and from the acromion to its distal tendon. Insertions of the
brachialis muscle on the deltoid tendon are detached to free the tendon from the humerus completely. The posterior border of the deltoid muscle is then dissected, which requires ligation of a constant vascular pedicle coming from the posterior circumflex humeral vessels to the skin. When the entire surface of the deltoid is exposed, delineating the amount that should be transferred is possible with the vertical line that follows the muscular fibers and is located somewhere between the posterior third and the anterior half of the muscle (Fig. 2B). At its lower end, this line runs centrally on the deltoid tendon. The whole posterior half of the tendon is harvested down to the bone; however, lengthening it with a periosteal flap is not necessary. The tendon is stripped away from the humerus from its distal to its proximal parts, which is progressively visible at the deep aspect of the deltoid. Once the tendon has been detached, the deep aspect of the muscle is exposed gradually until it is possible to locate the posterior circumflex vascular pedicle and its branches for the posterior part of the deltoid at the proximal third of the muscle. Together with the pedicle is the axillary nerve and its branches for the muscle. A careful dissection of the neurovascular pedicle is required before pursuing the separation of the posterior part of the muscle up to this pedicle, which must be left intact (Fig. 2C).

When dissection has been completed, excursion of the tendon can be measured at approximately 3 cm. To prevent adhesions, two or three absorbable stitches are placed between the lateral head of triceps and the remaining part of the deltoid tendon, covering the bare area of humerus where the posterior deltoid tendon was inserted. A synthetic ligament (polyethylene terephthalate, 750 mm long, 5.2 mm wide) is then interwoven at least three times in the deltoid tendon at the its deep aspect. The tendon is first transected transversally at its most proximal part, and then the ligament is passed through it until it reaches its middle point (Fig. 2D). Each of the ends of the ligament is then passed through another transversal transection of the tendon, so that it crosses the mid-axis of the tendon. The same maneuver is performed a third time, in a more distal transversal transection of the tendon. Finally, when both ends of the ligament have the same length (Fig. 2E), they are pulled distally, and the ligament is secured firmly to the deltoid tendon by multiple nonabsorbable sutures.

The second part of the procedure is performed with the elbow in full extension, arm abducted on the hand table. From then on, anteposition of the arm is forbidden. The two ends of the synthetic ligament are interwoven at least three times in the triceps tendon, which is pulled proximally with a forceps (Fig. 2F). Tension of the transfer must be at the maximum in such a way that gentle passive flexion of the elbow cannot exceed 30° to 40° with the arm adducted and 40° to 60° with the arm abducted at a right angle. Numerous nonabsorbable 3-0 sutures secure the ligament into the triceps tendon. The ligament is covered on its entire length by the paralyzed triceps muscle, which is sutured to itself over the transfer, separating it from the skin (Fig. 2G, H). The skin is sutured in two planes on two suction drains. A well-padded, long-arm, fiberglass splint is applied, holding the elbow in 10° of flexion and the wrist in 30° of extension. The shoulder is left free; however, its adduction and anteposition are forbidden to prevent stretching of the transfer. Postoperative management is the same as for the biceps transfer.

Wrist and hand

Tenodesis effect at the elbow

In tetraplegic patients, the BR and ECRL are usually the only transferable muscles below the elbow. Because their proximal insertions are located on the humerus, elbow extension automatically produces traction on their musculotendinous unit and leads to tenodesis effects [22]. To assess this phenomenon, the authors designed a clinical and anatomic study [23] in which BR and ECRL tendons were divided at their distal insertion. Their muscular bellies were dissected completely up to the radial recurrent vessels, and a distal traction was applied to the tendons in such a way that stretching of the muscular belly was maximal during the whole procedure. Position of the tendon was recorded first with the elbow at 90° of flexion, then in full extension. Extension of the elbow produced traction on the BR and ECRL that led to a proximal displacement of their tendons. The farther the muscle was inserted from the rotation axis of the elbow, the longer its proximal shifting: between 90° and 0° of elbow flexion, mean tendon excursion was 32 mm for BR and 19 mm for ECRL.

This elbow-related tenodesis effect prompts the authors to emphasize three points in tetraplegic patients:

1. BR and ECRL transfers should be immobilized postoperatively in 90° of elbow flexion to decrease their tension optimally during the healing period.
2. Because surgical rehabilitation of elbow extension requires a postoperative immobilization in full extension, it should not be performed at the same time as BR or ECRL transfers.

3. As stressed by Brys and Waters [24], active elbow extension should be restored before BR or ECRL tendon transfers to control their tension actively.

Moreover, the authors believe that the tension of the BR and ECRL transfers should be set intraoperatively with the elbow flexed at 90°. They have observed that wrist-related tenodesis effects are the same intraoperatively with the elbow flexed at 90° and at 3 months postoperatively with the elbow fully extended. The authors believe, therefore, that the usual postoperative slackening of the BR and ECRL transfers corresponds approximately to the tenodesis effect at the elbow. To some extent, this tenodesis effect at the elbow applies to any forearm muscle inserted on the humerus. For these muscles, the authors set the tension of transfers in such a way that (1) elbow-related tenodesis effects are eliminated by flexing the elbow at 90°, and (2) wrist-related tenodesis effects work properly (ie, the hand opens when the wrist is flexed and closes when the wrist is extended).

Brachioradialis

The BR is the first possible transferable muscle in tetraplegia. It is the most versatile motor and is used to restore wrist extension (International Classification [IC] group 1), finger extension, and finger or thumb flexion (IC groups 2–8) (Table 1). Whatever the destination of the BR, the surgical technique is basically the same, with the most important point being to free the muscle completely from its fascial connections up to the elbow to get approximately 30 mm of excursion.

According to Zancolli [4], transfer of the BR to the extensor carpi radialis tendons was proposed by Vulpian and Stoffel in 1920. In tetraplegia, this was first proposed by Wilson [22] and first described fully by Freehafer [25].

The functional results of BR transfers have been discussed extensively [26]. In the authors’ experience (59 cases), BR is an efficient transfer medium, except when it is to the extensor digitorum communis (EDC) where results are rather unpredictable. According to Ottonello and Leclercq [27], the poor results of BR to EDC transfers seem to be related to paralysis of the flexor carpi radialis, and they do not recommend performing it in patients in IC groups below 5. The authors, however, have obtained some good results when the flexor carpi radialis was paralyzed.

**Techniques: Pneumatic tourniquet.** The skin is incised in a lazy S that extends from the elbow to the wrist at the radial side of the forearm. The tendon of the BR is found easily, as is the superficial branch of the radial nerve at its dorsal border. This nerve and its terminal branches must be dissected carefully and protected. The surrounding fascia and peritenon are incised longitudinally, and the

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\a The “×” indicates the most common active tendon transfers when the motor is available; except for the elbow, a tenodesis procedure is always possible.
muscle is dissected. Its terminal tendon is divided as distally as possible under the abductor pollicis longus (APL) and the extensor pollicis brevis, and the dissection is carried upwards at the deep aspect of the muscle. Some transversal branches coming from the radial vessels are ligated. The muscle must be freed entirely from its fascia to the level of the radial recurrent vessels, which comprise the main vascular pedicle of the BR and ECR muscles [14]. These vessels usually are located transversally on the deep aspect of the muscle just distal to the elbow flexion crease; avoiding injury to these is of utmost importance.

Once the BR has been dissected completely, the recipient tendon is exposed. The long radial skin incision provides an easy approach to the dorsal compartment (ECRL, extensor carpi radialis brevis [ECRB], EDC, extensor pollicis longus [EPL]) and the volar compartment (flexor digitorum profundus [FDP], flexor pollicis longus [FPL]) of the forearm. Whatever the recipient tendons, it is important (1) to dissect them from their fascias and synovial sheaths (from the musculotendinous junction down to the level of the wrist), and (2) to adjust the tension of the BR transfer with the elbow flexed at 90°.

In IC group 1 patients, the BR is sutured either to the ECRB or to both radial wrist extensors, because transfer to the ECRL alone causes more radial deviation than wrist extension [25]. To prevent rupture of the BR-to-ECRB transfer, the authors suggest the following procedure. The BR is transferred only to the ECRB via the classical way (ie, the BR tendon is interwoven three or four times in the ECRB tendon and sutured by multiple non-absorbable stitches) (Fig. 3C). The ECRL then is sutured longitudinally to the transfer, which is reinforced strongly by this continuous tendon, which has not been weakened by slits (Fig. 3D). Tension is adjusted so that the transfer spontaneously holds the wrist in slight extension (0°–20°) and that a slight passive flexion remains possible up to approximately 30°.

When the BR is transferred to the EDC and EPL (Fig. 3A), its tendon is first interwoven in the four tendons of the EDC (two or three passages) and then in the EPL tendon (2 or 3 passages). Afterward, it is looped back and sutured to the transfer. The tension is set to allow (1) a complete flexion of the finger MP joints and a thumb-to-index key pinch remain possible when the wrist is extended fully, and (2) the MP joints to begin to extend in the early stages of wrist flexion, which also leads to a reposition of the extended thumb.

Transfer of the brachioradialis to the flexor digitorum profundus or the flexor pollicis longus.

When “lassos” have been performed in a previous stage (see the next section), pulling each FDP tendon proximally is important to check for possible adhesions in the lasso areas and to free them with a blind, closed tenolysis (Fig. 3E). Suturing all the FDP tendons together at the level of their musculotendinous junction is useful to adjust their relative tensions so they reproduce the cascade of finger flexion (Fig. 3B). The BR tendon is first woven in the FDP tendon (two or three passages) and, if required, in the FPL tendon (two or three passages). Afterward, it is looped back and sutured to the transfer. The tension is adjusted to allow (1) passive flexion of the wrist and thus extension of the fingers and opening of the key pinch, and (2) extension of the wrist and thus flexion of the fingers and closing of the key pinch.

Finally, the tourniquet is released, hemostasis is secured, two suction drains are placed, and the skin is sutured. A well-padded fiberglass cast holds the elbow in 90° of flexion. The position of the wrist depends on the transfer: 30° of extension for a BR-to-ECRB or BR-to-EDC-and-EPL transfer, 30° of flexion for BR-to-FDP/FPL transfer. Active exercises and training of the transferred BR can be started 4 weeks after surgery, with the wrist being supported further in a splint for 3 weeks when the BR had been transferred to the wrist extensors [25]. In the first phase, the BR is trained in its new function via active flexion of the elbow against passive resistance (eg, in a splint) [4]. The second phase is intensive occupational therapy.

Extensor carpi radialis longus

Wrist-related tenodesis effects are well known: wrist flexion opens the hand, and wrist extension closes of the hand. These effects are maximal when the range of motion of the wrist is normal and when the viscoelasticity of the forearm muscles is normal (short spinal cord injury segment [11]). They are the key point of any functional surgery in a paralyzed hand. Actually, only active wrist extension is required to achieve these tenodesis effects [22,28], because flexion of the wrist can be passive (ie, caused by gravity when the patient can sit and the forearm can be pronated). Active extension of the wrist, therefore, is of utmost importance for the tetraplegic patient. When lacking, it can be restored if the BR is at least grade 4, as previously demonstrated. When present, it must not be impaired or weakened. Consequently, the ECRL must not be used as a motor in IC group 2 patients, in whom
active extension of the wrist is weak and depends only on the ERCL. It can be used as a motor only in patients in IC groups 3 and above, in whom active extension of the wrist is strong and depends on both the ECRL and ECRB.

Two problems can occur in these cases: (1) the distinction between IC groups 2 and 3, and (2) the possible simultaneous use of the ECRL and ECRB. Although many techniques for testing these two muscles separately have been published, the authors have witnessed that clinical examination alone is sufficient to distinguish between patients in group 2, in whom extension of the wrist is weak either at the first attempt or at repeated
attempts, and those in group 3, in whom no attempt of the examiner can overcome extension of the wrist regardless of the number of attempts or their duration. If any doubt remains in spite of repeated examinations, then the upper limb must be classified as a group 2 and the ECRL must be left intact.

The ECRL is the best motor for transfer to the FDP and FPL, because it is synergic and because the tenodesis effect that is related to active wrist extension via the remaining ECRB adds approximately 2 cm of tendon excursion [28,29].

**Technique.** The skin incision is the same as in the BR transfer. Branches of the superficial radial nerve must be dissected and protected. The tendon of ECRL is divided as distally as possible at the level of its insertion on the second metacarpal and then extracted proximal to the APL tendon. Dissection is performed proximally, and the muscle is freed entirely from the surrounding fascia to the recurrent radial vessels. The rest of the procedure is the same as described for the BR-to-FDP/FPL transfer, except for the postoperative rehabilitation, which is far simpler because of the synergy between wrist extensors and finger flexors.

**Other active transfers**

**Extensor carpi radialis brevis.** In IC groups 3 and above, an extensor carpi radialis muscle can be used as a motor. If the ECRB is used, the wrist extension caused by the remaining ECRL is associated with a radial deviation of the wrist. Thus, the ECRL usually is chosen as the motor. Nevertheless, when the ECRL is transferred, using the ECRB as a motor in a side-to-side suture with the FPL is possible. Although effective, this procedure can lead to a rupture of the ECRB as observed in 2 of the authors’ 16 cases. Even if it could be reduced to the minimum risk by meticulous surgical technique and extra precautions of immobilization, a chance still exists.

The authors believe that the rupture of ECRB is the most serious surgical complication that can occur in a tetraplegic patient when the ECRL has been transferred previously, because it results in a dramatic loss of grasp and pinch. Moreover, surgical treatment of this rupture by tendon graft is difficult and its results are worse than those obtained when the ECRB is intact. For these reasons, not only do the authors advise against the side-to-side suture of the ECRB to the FPL anymore but they also oppose using the ECRB in any procedure in tetraplegic patients to prevent the slightest risk of its rupture.

**Extensor carpi radialis intermediialis.** Supernumerary extensor carpi radialis tendons or muscles were described by Wood (as quoted by Zancolli [4]) in the late 19th century. There are two types of anomalies: accessory tendinous bands, which are the most frequent but useless for transfers, and the intermediate radial muscle, which is a small muscle found between the muscular bellies of the ECRL and ECRB. When present, this “extensor carpi radialis intermediialis (ECRI) muscle,” can be transferred to the FPL with the advantage of providing an independent function to the thumb [4]. In an anatomic study, the authors found an ECRI muscle in 2 of 50 dissections (4%) [14], whereas Leclercq (as quoted by Hentz et al. [30]) found it in 26 of 104 cadaver dissections (25%); in 15%, the ECRI was large enough for transferring.

Clinically, the authors have used the ECRI for transfer in 6 of 65 (groups 3 and 5) active or passive FPL reactivations. Usually, the postoperative adhesions between the ECRI-to-FPL and ECRL-to-FDP transfers have made them function together; however, in some cases, active pinch is actually independent of the finger flexion. Consequently, each time the authors find the ECRI muscle in patients in IC groups 3 to 5, they transfer it to the FPL tendon during the second operative stage (i.e., the flexor phase).

**Pronator teres.** When the PT is active (IC group 4 and above), it can be transferred to the FPL; however, the PT is usually too short to be attached securely to the proximal thin part of the FPL tendon (even if it is lengthened with a strip of periosteum from the radius) (Fig. 4A). Consequently, a tendon graft usually is needed to reinforce the transfer. This graft can be harvested in the same forearm; the APL tendon is a good choice. Before performing the transfer and the tendon graft, the authors recommend dividing the FPL tendon from its muscular fibers. These fibers can be spread and sutured so that they completely cover the bare area of radius where the periosteum was removed along with the PT. This reduces the risk of bony adhesions caused by the transfer (Fig. 4B). Because the PT is inserted proximally on the medial epicondyle of humerus, transfer adjustment must be performed with the elbow flexed at 90°. In this position, the tension of the transfer is such that wrist-related tenodesis effects work correctly (i.e,
the pinch opens when the wrist is flexed and closes when it is extended).

**Extensor digitorum communis.** In IC group 6 patients, there usually is active extension of the three ulnar fingers, but not of the index finger. A side-to-side suture of the EDC of the index finger to the rest of the EDC tendons, therefore, is indicated at the level of the distal forearm [4]. The authors associate this procedure with the two described in the following sections.

**Extensor digiti minimi.** The extensor digiti minimi (EDM) is usually active in IC group 6 patients, in whom it can be transferred to the paralyzed EPL. Two skin incisions are needed. The first, made longitudinal over the dorsal aspect of the MP joint of the little finger, allows division of the EDM tendons at this level. The second, made longitudinal along the ulnar border of the distal forearm and wrist down to the level of the pisiform (Fig. 5A), provides good exposure of the dorsal side (extensor carpi ulnaris [ECU], EDM, EDC, EPL) and the volar side (flexor digitorum superficialis [FDS]) of the distal forearm. After distal division, the EDM tendons are extracted and transferred to the EPL tendon where they are interwoven three or four times. The tension of the transfer is adjusted so that wrist flexion leads to thumb retro-position and that closing of the pinch remains possible when the wrist is extended. Because the EDM is inserted proximally on the humerus, a 90° flexion of the elbow is required for setting the transfer intraoperatively and for postoperative immobilization. The same applies to the ECU.

**Fig. 4. PT-to-FPL transfer.** (A) The PT tendon is detached with periosteum and held by the right forceps. The FPL tendon is held by the left forceps. The APL tendon, obliquely located at the distal forearm, has been harvested. (B) The top retractor shows the PT-to-FPL transfer reinforced by tendon graft. Detached from their tendon, the FPL muscular fibers have been spread and sutured to the bare area of radius where the PT was inserted. The bottom retractor shows the ECRL-to-FDP transfer. These transfers are close to each other and thus are prone to adhesions.

**Fig. 5. ECU-to-lassos and EDM-to-EPL transfers.** (A) Longitudinal incision along the ulnar side of the distal forearm allows exposure of the ECU tendon (bottom forceps), the EPL tendon (retractors), and the palmar aspect of the forearm. A small incision on the dorsal aspect of the hand allows distal division of the EDM tendon. (B) Transfers have been completed between the ECU and the FDS (bottom) and between the EDM and the EPL (top).
Extensor carpi ulnaris. The ECU is active in patients in IC groups 6 and above and can be used as a motor to activate lassos (ie, the indirect lasso technique) [4]. The main difference between group 6 and higher groups is the number of operative stages. Extension of the index finger and the thumb must be restored in group 6 patients, which requires a postoperative immobilization in extension that conflicts with the flexed position required after flexor restoration. To perform a FDP blind (closed) tenolysis during the second stage, the authors perform indirect lassos during the first stage, with a compromising immobilization position (ie, the wrist neutral and the MP flexed). In IC groups 7 to 9, only one stage is needed, in which the authors like to immobilize the wrist at 20° to 30° flexion associated with 90° flexion of the elbow and 60° to 70° flexion of the MP joints.

Technique. The lassos are performed first using the technique described below in the section on Passive tendon transfers. The FDS tendons then are exposed at the level of the distal forearm through the longitudinal ulnar incision, as described previously. The plane of dissection is located posterior to the FCU between the ulna and the ulnar neurovascular pedicle. The tendon of ECU is divided as distally as possible near its bony insertion and then dissected proximally. Afterward, the muscle is freed completely from its fascia up to the middle of the forearm (Fig. 5A) and then transferred to the FDS tendons, in which it is interwoven two or three times and sutured (Fig. 5B). The tension of the transfer is adjusted with the elbow flexed at 90° in such a way that complete extension of finger MP joints occurs during wrist flexion.

Flexor carpi radialis. Although gravity may be sufficient, wrist-related tenodesis effects are optimal when wrist flexion is active. Because of the importance of active wrist flexion in hand opening, the authors do not recommend using the flexor carpi radialis for a transfer when it is active (IC group 5 and above).

Passive tendon transfers: tenodeses

Because of the lack of active motors in tetraplegia, passive tenodesis procedures are required in IC groups 1 to 5 and involve primarily the tendons of the FDS (lassos), EDC, EPL, FPL, and APL. A few other tenodeses, such as FDP tenodesis, are used occasionally.

Passive direct lassos

The lasso technique was described by Zancolli [4]. Even when the FDS is paralyzed, the lasso technique usually prevents the claw deformity, so long as that muscular trophism and elasticity are preserved, a situation that occurs when the extent of spinal cord injury is short [11,31]. The results, however, are rather unpredictable when the FDS is paralyzed. In some cases, the procedure is inefficient, especially when there is MP joint laxity.

Technique

The skin incision is palmar and transversal, 1 cm distal to the distal palmar crease, from the radial to the ulnar side of the hand. Some superficial short incisions are made transversally as landmarks for skin closure. The proximal skin flap is elevated with the mid-palmar fascia, dividing vertical paratendinous septa up to the superficial palmar vascular arch. The synovial sheath of each finger flexor then is removed proximally to the A1 pulley, which is left intact. Each FDS tendon is freed from the corresponding FDP and from the synovial sheath. To reduce subsequent adhesions, great care is taken during the whole procedure to avoid any injury to the FDP tendons. Distal dissection is carried along the longitudinal axis of each finger just superficial to the flexor tendons sheath.

A curved mosquito forceps is introduced, end up, distally under the A1 pulley to localize the C1 pulley at the distal edge of A1. The tendon sheath is opened at this level, in an L shape, transversally along the distal edge of A1 and longitudinally toward the flexion crease of the PIP joint. The finger is flexed slightly, the skin is retracted distally, and the FDS tendon is pulled out so that it can be distinguished clearly from the FDP. It is then elevated with a stitch to minimize injury and to prevent its proximal retraction under the A1 pulley. The two slips of the FDS are divided as distally as possible with little, blunt, curved scissors. Each FDS tendon and its two slips must be freed entirely from surrounding attachments, either the vincula or synovial sheath, and must glide freely under the A1 pulley. The two slips of the FDS are divided as distally as possible with little, blunt, curved scissors. Each FDS tendon and its two slips must be freed entirely from surrounding attachments, either the vincula or synovial sheath, and must glide freely under the A1 pulley. The same procedure is performed for each finger. Usually, the FDS to the little finger is thin, as is its A1 pulley when present. A flat retractor (Farabeuf type) is placed successively under each FDS at the proximal part of the A1 pulley to protect the FDP from needles and forceps. Each FDS is looped around the A1 pulley and simply sutured back into itself proximally with
three separate 3-0 nonabsorbable sutures. Each stitch is passed twice through the tendons. The distal stitch may include a part of A1 pulley. Tension of the transfer is set so that automatic MP extension remains possible during wrist flexion and so that the MP joint automatically and progressively flexes when the wrist is extended passively. The tension is increased gradually from index to little finger to restore physiologic MP positions. The position of the index finger’s MP joint must be checked carefully so that a key pinch with the thumb has been made possible.

After completing other procedures associated with the lassos, the tourniquet is released and hemostasis is performed. The skin is approximated with interrupted nylon stitches. The authors do not place any drainage in the palm. Postoperative immobilization includes 20° or 30° of wrist flexion, 60° to 70° of MP joints flexion, and must allow complete fingers flexion. The aim of immediate daily postoperative physiotherapy is to prevent adhesions of flexor tendons by passive flexion-extension motion of the IP joints. After a 4-week immobilization, the aim of physiotherapy is to recover the preoperative range of motion of the wrist and MP joints.

Despite all intraoperative and postoperative precautions, adhesions of FDP tendon in the MP area are almost inevitable. This is the reason why the authors always perform the lasso procedure during the first surgical stage (extensor phase), thus making an FDP blind (closed) tenolysis possible during the second stage (flexor phase).

Extensor digitorum communis tenodesis

Tenodesis of the EDC is a direct dynamic tenodesis [32]. Both extremities of the tendon are posterior to the flexion-extension axes of the wrist and finger MP joints. Flexion of the wrist activates the MP joint extension. The only biomechanical requirement is to fix the EDC tendons dorsally and proximally to the flexion-extension axis of the wrist, which is located at the proximal part of the capitatum. Most surgeons fix them to the distal radius [4,33], which is a difficult technique. An alternative is to fix the EDC to the extensor retinaculum of the wrist, which anatomically fulfills the basic requirement. Although this procedure is being performed, it has never been published. The authors have used the technique since hearing its description from Jacques Teissier (personal communication, 1997), who has been using it for a long time.

Technique

The skin incision is curved gently at the radial side of the wrist, starting in the anatomic snuffbox and extended for approximately 10 to 12 cm in a line convex to the radial side of the wrist. The incision is designed to perform a carpometacarpal joint arthrodesis of the thumb in the same stage (if needed) and to be extended proximally in the second stage for transfer of the BR to the flexor tendons. The branches of the radial nerve must be protected. The superficial veins are raised with the skin flap, which is dissected all the way to the ulnar head.

The distal edge of the extensor retinaculum is easy to locate. Distal from this edge, the loose dorsal fascia over the metacarpal area is removed 3 to 5 cm, as is the synovium of the EDC tendons.

The proximal edge of the extensor retinaculum is often difficult to distinguish from the antebrachial fascia. Visible or not, the purpose is to leave a band of retinaculum 3 to 5 cm wide proximally from the distal edge. The dorsal antebrachial fascia is removed proximally, and synovectomy of extensors tendons is performed (Fig. 6A).

Each EDC tendon is detached from its muscular belly. A mosquito forceps is introduced under the extensor retinaculum distally, grabbing the detached tendon and pulling it proximally under the retinaculum (Fig. 6B). Finally, each tendon makes a double loop around the extensor retinaculum and is sutured to itself at the carpal level. Tension should be set so that complete MP flexion of the fingers remains possible in wrist extension and so that MP joints begin to extend in the early stages of wrist flexion, starting at neutral [4].

This technique allows the tension for each EDC tendon to be set separately. It must be completed by a classical single loop tenodesis of the EPL and, ideally, the EDM tendons around their respective osteofibrous tunnels (Fig. 6C). Postoperative care requires a 4-week immobilization of the wrist in extension before starting physiotherapy.

We have performed this procedure in 10 cases, all of which were in IC group 2 patients. Results were good in some cases, with extension of the MP joints being almost complete when the wrist was flexed. Usually, however, passive opening of the hand was limited. Obviously, whatever the structure with which the authors choose to perform EDC tenodesis (radius or retinaculum), there was a limitation of MP extension due to the lack of motors for wrist flexion. The situation, however, is even more complex because of
the shortening of finger flexors and because MP flexion is not controlled actively, resulting in extrinsic swan-neck deformities when the lassos are too tight or when the FDS is spastic. Additionally, there is the reciprocal tenodesis effect, in which active flexion of the fingers leads to an extension of the wrist. Despite these complications, when an EDC tenodesis is indicated, the authors still recommend fixing it to the extensor retinaculum, because this is as effective as and easier than fixing it to the radius.

*Extensor pollicis longus, abductor pollicis longus, and flexor pollicis longus tenodeses*

Although usually associated with EDC tenodesis, a separate EPL tenodesis is possible. After being detached from its muscular belly, the tendon is looped distally around its osteofibrous tunnel at the level of the distal radial epiphysis and then sutured to itself distal to the tunnel. The tension is adjusted by moving the wrist, with extension allowing the closing of the key grip and flexion leading to thumb retroposition. If the functional result of EPL tenodesis is unsatisfactory, increasing its tension during the second stage (flexor phase) is possible without weakening the tendon. This can be accomplished by detaching the APL tendon from its muscular belly, looping back its proximal part around its osteofibrous tunnel and then around the EPL tenodesis, and finally suturing it to itself under tension (Fig. 6D), creating an EPL–APL tenodesis.

Another effective procedure that the authors use in IC group 1 patients is the EPL–FPL tenod-

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**Fig. 6. EDC tenodesis to the extensor retinaculum and EPL tenodesis.** (A) The retinaculum has been dissected, the dorsal forearm fascia has been removed, and synovectomy has been completed on the EDC and EPL tendons, with the latter tendon being oblique. The sensory branch of radial nerve is retracted (top). (This panel depicts the right upper limb, with the forearm on the right and the hand on the left.) (B) Each EDC tendon is detached from its muscular belly, and its proximal end is passed under the extensor retinaculum before being sutured to itself distally. (C) EDC tenodesis and EPL tenodesis have been completed. Detached from its muscular belly, the EPL tendon is looped back around its osteofibrous tunnel and sutured to itself. (D) APL tenodesis is performed to increase tension of the EPL tenodesis that was completed in a previous surgical stage. APL tenodesis is horizontally U-shaped around APL osteofibrous tunnel. The upper part of the horizontal U is sutured under tension to the EPL tenodesis. The lower part of the U is the APL tendon sutured to itself. (This panel depicts the left upper limb, with the forearm to the left and the hand to the right.)

Fig. 7. Allieu’s EPL-to-FPL tenodesis. (A) A transversal bony tunnel is made at the radial side of the distal radius exposed by the retractor. (B) The EPL and FPL tendons are detached from their muscular bellies. The EPL tendon is passed through the tunnel from dorsal to volar (bottom forceps). The FPL is passed through the tunnel from volar to dorsal (top forceps). (C) The EPL and FPL tendons are sutured to each other under proper tension.

Fig. 8. Distal split FPL tenodesis. (A) Bayonet incision at the radial side of the thumb. (B) Right oblique forceps holds the proximally attached FPL slit. The other half of FPL tendon remains intact. Left horizontal forceps holds the distally attached EPL slit. The other half of EPL tendon remains intact. (C) Tenodesis is completed. The tension must be the same on both slits of FPL.
Split distal flexor pollicis longus tenodesis

The split distal FPL tenodesis described by Mohamed et al. [34] is an alternative to IP arthrodesis for the prevention of excessive flexion of the thumb's IP joint during the key grip.

Technique

The authors perform this procedure through a bayonet incision along the dorsal IP crease, the radial aspect of the proximal phalanx, and the palmar IP crease (Fig. 8A). The dorsal skin flap is raised with the superficial veins along the EPL tendon. Palmar dissection is made along the fibrous sheath of the FPL. Great care must be taken to preserve the dorsal sensory branches and the radial palmar neurovascular bundle. The sheath of FPL is opened transversally along the distal border of the proximal pulley at the MP level and then longitudinally at its radial border down to the distal insertion of the tendon. The FPL is extracted and split longitudinally; its ulnar half is left in place, and its radial half is detached distally, routed dorsally, and sutured to the EPL tendon (Fig. 8B). Specifically, the authors find it easier to suture it to the radial half of EPL, which has been divided proximally and left attached distally. The tension of the tenodesis must be adjusted carefully to achieve a neutral IP joint position with the same tension on both halves of the FPL tendon (Fig. 8C). Immobilization of the extended IP joint with an axial K-wire may be useful during the healing period of the tenodesis.

Summary

The techniques of the tendon transfers that are used primarily for the functional rehabilitation of upper limbs in tetraplegia are described in this article. The restoration of active elbow extension can be obtained either by biceps-to-triceps or by deltoid-to-triceps transfers. Grasp and key grip can be restored either by active or by passive tendon transfers. The usual motors of active transfer are the BR and ECRL. The usual tenodeses involve the FDS (via lassos), EDC, EPL, FPL, and APL.

References


