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Recent advance

Tendon transfer surgery for radial nerve palsy

Chirurgie des transferts tendineux pour paralysie radiale

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ABSTRACT

Palliative tendon transfer is an integral part of radial nerve palsy treatment. It can be considered in the first weeks when the possibility of nerve repair by direct suture or nerve grafting is not feasible or reasonable. Mostly, it is discussed secondarily when it is too late for nerve surgery and motor recovery cannot be expected, or after failure or incomplete recovery after nerve repair. The goal of tendon transfers is to restore wrist, finger and thumb extension. For wrist extension, the use of pronator teres is well accepted. The best tendon transfer for finger extension is debated. This can be restored doing a flexor carpi ulnaris (FCU), flexor carpi radialis or flexor digitorum superficialis (FDS) to extensor digitorum communis transfer. Regarding thumb extension and abduction, a palmaris longus (PL) or one FDS tendon to the rerouted extensor pollicis longus (EPL) transfer can be performed. If a transfer is done on the EPL without rerouting it, abduction can be restored by doing a tendon transfer to the abductor pollicis longus (APL) or an APL tenodesis. The different tendon transfer options are selected based on the surgeon's preference, and most importantly, discussed with the patients to define the objectives together. The transfer is chosen based on the clinical examination (high or low radial nerve palsy, tendon available for transfer like PL, wrist mobility) and based on the patient's needs and expectations (activities requiring the FCU, finger independence, independence of thumb extension or abduction). If the surgical rules and the postoperative instructions for rehabilitation are followed, tendon transfers for radial nerve palsy regularly produce very satisfactory results.

Mots-clés:
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RÉSUMÉ

Le traitement palliatif par transfert tendineux fait partie intégrante du plan thérapeutique d'une paralysie radiale. Il peut être discuté dans les premières semaines, si les possibilités de réparation par suture ou greffe nerveuse ne sont pas réalisables ou raisonnables. Il est surtout discuté secondairement, en cas de lésion prise en charge trop tardivement ou après échec ou récupération incomplète après chirurgie nerveuse. Le but du traitement est de réanimer l'extension du poignet, des doigts longs et du pouce. L'utilisation du pronator teres pour réanimer l'extension du poignet fait l'unanimité. Le meilleur transfert pour la réanimation de l'extension des doigts reste controversé. Elle peut être réanimée par un transfert du flexor carpi ulnaris (FCU), du flexor carpi radialis ou du flexor digitorum superficialis (FDS) sur l'extensor digitorum communis. Concernant l'extension et l'abduction du pouce, le palmaris longus (PL) ou un tendon du FDS peut être transféré sur l'extensor pollicis longus (EPL) rerouté. Si l'EPL réanimé n'est pas rerouté, l'abduction peut aussi être assurée par un transfert sur l'abductor pollicis longus ou par

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une ténodèse de ce dernier. Les différentes possibilités de transferts sont choisies en fonction des écoles, mais surtout discutées avec le patient et les objectifs définis communément ; le choix du transfert est décidé selon l'examen clinique du patient (paralysie radiale haute ou basse, présence des tendons transférable comme le PL, mobilité du poignet), et selon ses besoins et attentes (activités nécessitant le FCU, importance de l'indépendance des doigts, de l'indépendance de l'extension ou de l'abduction du pouce). Si les règles techniques de réalisation et les consignes de rééducation postopératoires sont respectées, les transferts tendineux pour paralysie radiale donnent régulièrement des résultats très satisfaisants.

1. Introduction

Radial nerve palsy is responsible for loss of extension in the wrist and finger metacarpophalangeal (MCP) joints and loss of thumb abduction and extension. These movements are essential for opening the hand before gripping an object and then releasing the said object. Moreover, grip strength is reduced because patients cannot stabilize their wrist in a neutral or extended position to maximize the excursion of the flexor tendons during gripping [1].

Two situations must be distinguished: high and low radial nerve palsy. High radial nerve palsy, secondary to a lesion of the radial nerve above the elbow is responsible for loss of wrist and finger (MCP joints) extension and loss of thumb abduction and extension. It is accompanied by loss of sensitivity in the territory of the superficial branch of the radial nerve (SBRN) that is often well-tolerated by the patient. Low radial nerve palsy is defined by a lesion of the deep branch of the radial nerve (DBRN), which terminates in the posterior interosseous nerve (PIN), secondary to a radial nerve lesion below the elbow and thus with no sensory damage. In this case, wrist extension is maintained because the innervation of the extensor carpi radialis longus (ECRL) is very proximal, before the division of the radial nerve into its deep and superficial branches, and thus is preserved. Therefore, the carpus goes into radial deviation during wrist extension. If the palsy is more distal, i.e. 5 cm or more from the lateral epicondyle, or if the motor branch of the extensor carpi radialis brevis (ECRB) comes from the SBRN [2], the innervation of the ECRB is preserved, and the radial deviation of the carpus during wrist extension is less visible, but still present given the extensor carpi ulnaris (ECU) paralysis. In fact, if the PIN is paralyzed, the latter is generally not functional given its very distal innervation, with a motor branch located at 8 cm or more from the lateral epicondyle and distal to the motor branch of the extensor digitorum communis (EDC) [3].

Palliative treatment by tendon transfer is an integral part of the treatment plan for post-traumatic radial nerve palsy. It can be discussed in the first few weeks, if suture repair or nerve grafting cannot be done or are not justified, for example if a very long nerve graft is required. There is no consensus about the maximum length of nerve graft for the radial nerve. In the literature, nerve grafts longer than 8 cm are associated with worse results. However, satisfactory results are regularly reported with nerve grafts up to 15 cm long [4]. Tendon transfer can also be proposed right away, if the nerve repair bed is of poor quality, if the initial nerve assessment suggests that the available nerve stock should be reserved to repair another nerve trunk, and/or if the subject is much older. It can also be combined with nerve surgery in cases of lesions of the posterior cord of the brachial plexus [5] and lesions of the plexus nerve roots, most often C7. In most cases, it is considered secondarily when the lesion is addressed too late (ineffective motor recovery after 12–18 months of denervation [6]), or after failure or incomplete recovery after nerve treatment [7].

The recovery time is calculated based on the principles outlined by Seddon. If radial nerve transection is not suspected, the patient is monitored for 3 months. Nerve palsy secondary to neurapraxia or 2nd or 3rd degree lesions in the MacKinnon and Dellon classification [8] most often recover spontaneously [9]. In case of nerve transection, there is Wallerian degeneration and after direct nerve suture or nerve grafting, the regeneration is slow and potentially incomplete. The rate is about 1 mm/day (slower in older patients and smokers) and the recovery time is estimated based on the distance between the nerve lesion and the effectors, with the brachioradialis (BR) being the first muscle reinnervated. The following muscles are subsequently reinnervated in this order: ECRL (above the elbow), the supinator, ECRB, EDC, ECU, extensor digiti quinti (EDQ) or minimi (EDM), abductor pollicis longus (APL), extensor pollicis longus (EPL), extensor pollicis brevis (EPB), and the extensor indicis proprius (EIP) [10]. An electromyogram can be used to detect early signs of reinnervation before a contraction is visible clinically [6]. The tendon transfer must be delayed enough to allow a reasonable amount of time for nerve recovery. The delay ranges widely from 6 to 18 months, depending on the studies [11]. Therefore, with a radial nerve lesion at the middle third of the humerus, one has to wait at least 6 months to detect signs of reinnervation [11,12]. Thus, it appears reasonable to delay the tendon transfer until this point [11]. The transfer will be done solely if the BR muscle is not reinnervated based on clinical and electromyographical criteria. Sunderland recommends a tendon transfer at 1 year if there are no signs of recovery [9].

While waiting for the surgical treatment, the range of motion of all the joints are maintained through self-mobilization and/or physiotherapy. A splint that keeps the wrist in a neutral position and keeps the first web space open can be worn during the day.

Tendon transfer can be discussed together with nerve repair to quickly restore wrist extension; in certain patients, its loss can be the source of major functional disability, but this is not our strategy. Along with the fact that a splint is not necessary, this transfer more rapidly improves hand function and restores grip strength while waiting for re-innervation of the wrist extensors [13].

2. Treatment goals and principles

The objective is to simultaneously restore active wrist extension in cases of high radial palsy, along with finger and thumb extension. Various transfers can restore these functions and there are several combinations of transfers that meet various selection criteria.

2.1. Possibility of transfer

2.1.1. Restoring wrist extension

Transfer of the pronator teres (PT) to the ECRB is a very reliable transfer to restore wrist extension. This is likely the most important function to restore in high radial palsy, especially since a permanent wrist flexion deformity is not well tolerated by patients. Using the PT as a donor muscle is not controversial. The advantages are its strength (1.2 kg) and its excursion (50 mm),

which are better than those of the ECRL (1.1 kg and 33 mm) and the ECRB (0.9 kg and 33 mm).

Harvesting the PT leaves few sequelae, since the pronator quadratus, which is innervated by the median nerve, ensures pronation. Also, the preservation of the muscle's initial course after the transfer continues to ensure its pronation action. However, recent studies have shown that there may be a moderate reduction in mobility and strength in pronation after tendon transfer [14]. The ECRB is preferred to the ECRL because its insertion is more central (based on 3rd metacarpal) and it provides more balanced radio-ulnar deviation during wrist extension.

The PT can also be transfer onto the ECRL and the ECRB; however, in this case, the ECRL is recentered on the ulnar portion of the base of the 3rd metacarpal [15] or on the 4th metacarpal [16], especially if the flexor carpi ulnaris (FCU) is used. According to Tubiana, this recentering of the ECRL is also justified because of the frequent intertendinous connections between the ECRL and ECRB in the forearm [17].

If the PT cannot be transferred, one of the tendons of the flexor digitorum superficialis (FDS) can be used [11].

2.1.2. Restoring thumb extension and/or abduction

Thumb extension can be restored by transferring the palmaris longus (PL) or one of the FDS tendons to the EPL.

Several options are available to restore thumb abduction:

- Rerouting the EPL when the PL is used as a motor. This will help to suppress the adducting action of the EPL, which is removed from its groove, in favor of an abduction action [18] and then will provide simultaneous thumb abduction and extension of the interphalangeal joint. The EPL, which is transected at its musculotendinous junction, is removed from its groove and positioned subcutaneously, laterally on Lister's tubercle by simply opening its groove. Tubiana criticized this technique described by Scuderi [18] because of insufficient retropulsion. For satisfactory retropulsion and abduction, he passes the EPL in the ECRL groove, which is left empty by its translocation at the base of the 3rd metacarpal (see below). Its new pulley prevents it from dislocating palmarly [15]. The EPL can also be rerouted in a retrograde manner through the 1st compartment after excision of one or more APL slips to allow sliding without difficulty [19,20]. EPL rerouting in a groove helps to prevent tendon bowstringing, which can be a side effect of PL transfer onto the EPL when wrist flexion and thumb extension are done simultaneously.
- Tenodesis of the APL tendon around the BR distal insertion. The EPB can be sutured to the EPL to stabilize the 1st metacarpal and to help prevent Z deformity of the thumb [21].

Procedures acting directly on the APL (transfer or tenodesis) help to prevent a zigzag deformity of the thumb column. If there is no PL, to restore the EPL, it is possible to use the muscle transferred on the EDC; however, in this case, independent thumb extension is lost. If we want to preserve it, it is preferable to use the FDS of the ring finger, a flexor carpi radialis (FCR) or a divided FCU [22]. In patients with low radial nerve palsy, the functional BR can also be transferred, but this tendon transfer is difficult to re-educate.

2.1.3. Restoring finger extension

Finger extension can be restored by the FCU, FCR or FDS.

The FCU is one of the first motor muscles used to restore extension of the MCP joints [23]. Its strength (2 kg) is superior to that of the extensors (1.7 kg), but its excursion is slightly less (33 mm versus 50 mm for the thumb and finger extensors). Alternatives have been proposed. According to Boyes, it is a more important wrist flexor than the FCR, since the axis of "normal" wrist movement ranges from radially deviated-extended position to ulnarly deviated flexed position (the dart throwing motion) [24]. Despite these considerations, clinical studies found no significant impact on wrist function after its harvesting [25]. FCU harvesting is potentially responsible for radial deviation. Thus, it is not recommended in cases of low radial nerve palsy, where there is an initial presentation of radial deviation of the wrist in extension (see below). To avoid the above-cited drawbacks, other motor muscles have been proposed such as the FCR [26] or the FDS [27].

The FCR is slightly less powerful, but its excursion is closer to that of the EDC [17]. Its harvesting does not destabilize the wrist in the frontal plane [6].

FDS transfer to restore finger extension generally consists of transferring the FDS III to the EDC and the FDS IV to the EPL and EIP [26]. The FDS IV can also be transferred to the EDC.

2.2. Combination of tendon transfers

There is disagreement about the best tendon transfer combination. Several transfers are possible. Cheah et al. described and classified some of them according to the donor muscle to restore the EDC: transfer using the FCU, FCR, FDS, transfer using the FCU or the FCR with thumb abduction reconstruction (transfer to the APL and/or EPB) and transfer using the FCU without restoring wrist extension (Table 1) [28].

Four typical transfers are currently used after radial palsy: these typical transfers are given as examples, since many variations are possible (type of EPL rerouting, associated APL tenodesis, etc.).

2.2.1. Transfer using the FCU with transfer on the APL (Merle d'Aubigné) [29]

It corresponds to the following: PT to ECRB, FCU to EDC + EIP + EPL, PL to APL + EPB. The drawback of this transfer scheme is the loss of independent thumb extension (EPL and EDC are restored by the same transfer) and the risk of inducing radial wrist deviation. However, the latter is not a given [30].

2.2.2. Transfer using the FCU with re-routed EPL and centralized ECRL (Tubiana) [15]

This transfer uses a PT to ECRB + recentralized ECRL transfer. To avoid radial wrist deviation, the ECRL is recentralized on the ulnar side of the 3rd metacarpal. The FCU is transferred to the EDC and EIP. The EIP is transected 4 cm proximal to the extensor retinaculum, taken out of the 4th compartment distally to the retinaculum to provide it with a superficial course, then the ECRL is passed into the 4th compartment, instead of the EIP. The PL is transferred to the EPL, which is rerouted in the groove of the ECRL [17]. This transfer can be done without centralizing the ECRL, but there is a risk of radial wrist deviation.

2.2.3. Transfer using the FCR with re-routed EPL (Starr, Tsuge) [31,32]

The PT is transferred to the ECRB, the FCR to the EDC and the PL to the re-routed EPL. As indicated previously, the advantage of the FCR is that it is not associated with radial deviation during wrist extension since the FCU is preserved.

2.2.4. Transfer using the FDS (Boyes, Chuinard) [24,27]

The PT is transferred to the ECRL and the ECRB, the FDS III to the EDC (through the interosseous membrane), the FDS IV to the EIP and EPL (through the interosseous membrane) and the FCR to the APL and EPB.

Restoring the EPL and EIP with the same tendon may appear contradictory to the principles of using one tendon for the same

Table 1
The various types of tendon transfers based on the muscle used as the extensor digitorum communis (EDC) donor, and whether dedicated thumb abduction and wrist extension reconstruction have been carried out (from Hand Clinics, vol 32(3), Cheah AE, Etcheson J, Yao J. Radial Nerve Tendon Transfers, page 327. Copyright 2016 with permission from Elsevier" [28]).

		Recipient tendon						
		Wrist extension		Finger extension		Thumb extension	Thumb abduction	
Type	Author,y	ECRB	ECRL	EDC	EIP	EPL	EPB	APL
FCU	Jones, 1916	PT	PT	FCU (III-V)	FCR	FCR	Nil	Nil
	Zachary 1946	PT	PT	FCU	Nil	PL/BR/FCU	Nil	Nil
	Said, 1974	PT	PT (ECU included)	FCU	FCU	PL/FCR	Nil	Nil
	Riordan, 1983	PT	Nil	FCU	Nil	PL	Nil	Nil
	Tubiana, 2002	PT	PT (ECRL centralized)	FCU	FCU	PL	Nil	Nil
FCR	Starr, 1922	PT	PT	FCR	FCR	PL	PL	PL
	Brand, 1975	PT	Nil	FCR	Nil	PL	Nil	Nil
	Tsuge, 1980	PT	PT [a]	FCR (IM)/FCU[a]	Nil	PL	Nil	Tenodesis
	Ishida & Ikuta, 2003	PT	Nil	FCR (IM)	Nil	PL	Nil	Tenodesis
	Lim et al, 2004	PT	Nil	Split FCR	Nil	Split FCR	Nil	Nil
	Al-Qattan, 2012	PT	Nil	FCR	FCR	FCR	Nil	FCR
FDS	Boyes, 1962	PT	PT	FDS III (III–V)	FDS IV	FDS IV	FCR	FCR
	Chuinard et al, 1978	PT	PT	FDS III (III–V)	FDS IV	FDS IV	FCR	FCR
	Krishnan & Schackert, 2008	PT	PT	FDS IV	FDS III (III–V)	FDS III (III–V)	Nil	PL
FCU/FCR with abduction reconstruction	Merle D'Aubigné, 1949	PT	PT	FCU	Nil	FCU	PL /FDS	PL /FDS
	Brooks, 1984	PT	Nil	FCU/FCR	Nil	FCU/FCR	PL	Nil
	Kruft et al, 1997	PT	PT	FCU	Nil	FCU	PL	PL
	Dunnet et al, 1995	PT	Nil	FCU/FCR	Nil	FCU/FCR	PL /FDS	Nil
FCU without wrist reconstruction	Kruft et al, 1997	Nil	Nil	FCU (II-V + EDM)	FCU	FCU	Nil	Nil
	Gousheh & Arasteh, 2006	Nil	Nil	FCU	FCU	FCU	Nil	Nil
	Monacelli et al, 2011	Nil	Nil	FCU	FCU	PL	Nil	Nil

BR: brachioradialis; *ECRL*: extensor carpi radialis longus; *ECU*: extensor carpi ulnaris; *EDC*: extensor digitorum communis; *EDM*: extensor digiti minimi; *EIP*: extensor indicis proprius; *FCR*: flexor carpi radialis; *FCU*: flexor carpi ulnaris; *FDS*: flexor digitorum superficialis; *PL*: palmaris longus; *PT*: pronator teres; *IM*: routed through the interosseous membrane.
[a] Previously, but no longer used to perform these transfers.

movement. However, concurrent thumb and index finger extension is useful for fine gripping and can be considered as the same function. The drawback is the risk of reduced grip strength and loss of independent middle and ring finger extension. This non-synergistic transfer requires more intense postoperative rehabilitation than the previously described transfers [33]. Contrary to the FCU and FCR and because of its large excursion (70 mm amplitude), it allows for simultaneous finger and wrist extension. In fact, to restore the extensors, 50 mm excursion is needed, and the carpal flexors only have an amplitude of around 33 mm [12]. Their active mobility will be increased by the tenodesis effect in wrist flexion (up to 30 mm excursion), making it possible to fully extend the MCP joints [6].

2.3. Other transfers

Another transfer described by Lim, which is useful if there is no PL, divides the tendons of the FCR or FCU into two strips to restore the finger extensors for the former and the EPL for the latter [22]. According to the author, double innervation of the FCR or FCU will allow independent finger and thumb extension.

If the FDS technique is chosen, some surgeons only use the FDS IV to the EDC to minimize the sequelae [15].

In rare cases of high radial nerve palsy with concurrent direct injury to the PT, FDS and PL muscles, Al-Qattan proposed using the FCR to restore wrist extension and the FCU to restore thumb and finger extension and thumb abduction [34]. In the four patients who underwent this transfer, the PT and FDS muscles were too weak to be transferred (due to partial muscle tissue loss) and scar adhesion, and not because of denervation. The PL was not found during the clinical examination, either because it was damaged or because of a congenital absence. After the transfer, there was major loss of wrist flexion strength, but all patients had good overall function.

2.4. Special case: tendon transfer after low radial nerve palsy (paralysis of DBRN)

Tendon transfers aim to restore finger and thumb extension but also to ensure balanced wrist extension in the frontal plane. In case of low radial nerve palsy, wrist extension is preserved and PT transfer is not necessary. However, it is associated with radial deviation because the ECRL or even the ECRB is (are) functional and the ECU is paralyzed (Fig. 1). This deviation is greater when the ECRB is paralyzed or weakened. Only the fingers and thumb extension are directly restored by the transfers [15].

The transfer principles are the same as those mentioned previously. However, using the FCU is not recommended given the risk of accentuating the wrist's radial deviation; the other types of transfers (FCR or FDS) are preferable. It is tempting to use the ECRL as a transfer to reduce the radial component, but one must first make sure that the ECRB is sufficiently active to allow full wrist extension, which is not always the case [15]. Hence, it is preferable not the use the ECRL. Several methods have been described to rebalance the wrist in the frontal plane:

- Recentering the ECRL insertion on the ulnar side of the base of the 3rd metacarpal medially to the ECRB insertion [15] is our preferred technique.
- It has been proposed to use a course that goes around the ulnar side of the forearm for the tendon transfer that restores finger extension. There is a risk of ulnar nerve compression if the FDS is passed on the ulnar side [35].

Fig. 1. Wrist extension with radial deviation due to incomplete radial palsy.

3. Selection criteria for tendon transfers

It is difficult to choose the most appropriate combination of tendon transfers. Selecting which technique to use is based on multiple criteria [36]. It is important to have a discussion with the patient about his/her needs and to set the objectives of the transfer. The choice is based on:

- whether the palsy is complete or incomplete: in cases of low radial palsy, using the FCU is not indicated because it will accentuate the wrist's frontal imbalance.
- the patient's functional demands: one must take into account the dominant side, the work and recreational activities
  - o For example, in a patient who uses a keyboard, FDS harvesting is not recommended as this would compromise finger independence. The independence of thumb extension is important for certain musicians; the independence of thumb abduction can be important in a patient who works on computer [28], this can guide the choice of transfers or the rerouting of the EPL if a PL to EPL transfer is planned.
  - o Harvesting the FCU may hinder those who perform manual labor [37], who are throwers or who need to swing a hammer (importance of the dart throwing motion).
- the patient's age, ability and motivation to follow a prolonged course of rehabilitation; transfers using the FDS often require lengthy rehabilitation, thus their indications should be limited to young, and highly motivated patients.
- the patient's clinical condition: PIP joints hypermobility may predispose the patient to the development of a swan-neck deformity after FDS transfer; conversely, the FDS has a large excursion and can be recommended in patients who have limited wrist mobility or all the more, wrist fusion and who cannot use the synergistic tenodesis effect in transfers involving the FCU and FCR [33].
- whether transferable muscles such as the PL are present.
- the presence of associated lesions which, in cases of severe and complex musculotendinous injury of the anterior compartment of the forearm, can limit the transfer options.

4. Technical considerations

4.1. General principles

No matter which method is chosen, the surgical principles are the same.

- The surgical approach must be long enough to easily harvest the motor muscles with sufficiently extensive release of their muscle belly to provide them with the most direct course possible. The transferred muscle must pass through the least number of incisions possible to prevent adhesions [6]. Also, the approaches must facilitate tendon suture and allow the release of adhesions around paralyzed muscles, or even to resect them partially, so they do not interfere with the excursion and course of the transfer.
- The EDC, EIP, EDQ and EPL tendons are exposed and the antebrachial fascia, thicker in its distal portion, can be resected so that the tendons and their sutures slide against the subcutaneous adipose tissue. To release the adhesions in the extensor compartment, the surgeon pulls on the tendons proximally to achieve complete extension of each finger individually [15].
- All the tendons must be harvested before any tendon suture is done.
- The tendon harvest sites – if they are not located in the approach of a suture – must be closed before tendon suturing.
- The tendon transfers for the fingers and thumb must be done first to allow for adjustment with the tenodesis effect [11,15].
- Hemostasis must be meticulous to prevent adhesions secondary to hematomas.

4.2. Transfer of pronator teres

Its harvesting is done through a lateral curved incision in the middle third of the forearm. The approach passes between the BR and ECRL. On the anterolateral side of the radius, the short pearly tendon of the PT is identified coming from the anterior side of the forearm. It is harvested flush with the bone while trying to extend it by a periosteal strip, giving more useful length for fixation (Fig. 2). The muscle belly must be properly released in the forearm to improve its excursion. Tendon suture is done to the ECRB at the musculotendinous junction, passing above the ECRL and the tendons are solidly fixed to each other. If the ECRL is not included in the suture, it is possible to harvest it as a tendon graft to reinforce the PT transfer on the ECRB [12]. During the fixation, the wrist is held in 40 ° extension with the PT under tension: the tension placed on the transfer must be such that the wrist is spontaneously maintained in very slight extension due to gravity [15]. If radial nerve recovery is not expected, some surgeons prefer to do end-to-end suture to make the transfer more effective (direct line of pull).

Fig. 2. The PT is harvested flush with the bone to elongate it with a strip of periosteum. The muscle belly must be properly released in the forearm to improve its excursion.

If the radial nerve has been repaired and recovery is possible, ECRB transfer is performed in an end-to-side fashion.

4.3. Restoring finger extension

4.3.1. FCU transfer

The FCU is harvested through a long incision to release its muscle body from the fascia, in order to provide it with the most direct course possible. The muscle fibers can insert very low on the tendon; thus it is preferable to resect them over a few centimeters. The tendon is transected at the level of the distal wrist crease. The muscle is then tunneled subcutaneously on the dorsal side of the forearm. The medial intermuscular septum can be partially resected to make sure it does not impede the tendon's course. The tendon suture to the extensors is done with a Pulvertaft weave, or by dividing the tendon into two slips over about 5 cm. An anterior one is passed obliquely in each finger extensor tendon about 5 cm proximally to the extensor retinaculum. The suture can be performed in an end-to-side fashion with the tendon at 45 ° without transecting the EDC or with a 2-cm resection of the EDC muscle, proximal to the suture, to reduce the angle at the level of tendon transfer suture. Moberg recommends opening the retinaculum to prevent ischemia of the extensor tendons and to reduce the angle of the traction axis [12] but this may lead to somewhat unsightly dorsal subluxation [15]. The wrist is held in 40 ° extension, with the fingers extended; the common and proper tendons are perforated one by one with tendon weaving forceps. They are then fixed solidly to the slip that transfixed them. This is a delicate step that will determine the harmony of finger extension; it must preserve the descending finger cascade from the index to the little finger (Fig. 3). To prevent MCP hyperextension in the little finger, the transfer does not involve the EDQ, except if the common extensor tendon of the fifth finger is too thin. The tenodesis effect is used to adjust the tension of the transfer: with the wrist extended, it must be possible to fully flex the fingers. If there is too much tension, the patient will not be able to recover full finger flexion, with the wrist straight or slightly flexed. With the wrist slightly flexed at 25 °, it is vital to achieve complete extension of the proximal phalanges. The 2nd FCU slip is then used to cover the tendons, to which it is fixed solidly, while readjusting the tension as needed.

4.3.2. FCR transfer

The FCR is simple to harvest as it has few proximal attachments. The incision is made on the anterior and radial side of the forearm. The radial artery, which lies on its radial side, and the superficial branch of the median nerve, which passes on the ulnar side of its terminal tendon, are identified and protected during the dissection. The tendon is transected at the level of the distal wrist crease. It is typically transferred with a course around the radial side of the forearm (Fig. 4) or by a direct course through the interosseous membrane as proposed by Tsuge [38]. A window is used to pass through the interosseous membrane that must be sufficiently wide and high enough to not impede the FCR's excursion. For a more direct axis of pull, Brand recommends doing an end-to-end tendon suture: the extensor tendons are transected, pulled distally and positioned superficially to the intact retinaculum [16]. End-to-side tendon suture proximal to the retinaculum is also possible [12]. Before transecting the extensors, one can place a temporary suture on the EDC to join them with adequate tension. The FCR can also be sutured to two good diameter EDC tendons, with the two other tendons being sutured to their neighbor(s) more distally. The author recommends suturing with the wrist and MCP in neutral position and the FCR under maximum tension [16]. The proper tension is verified through the tenodesis effect (see FCU transfer).

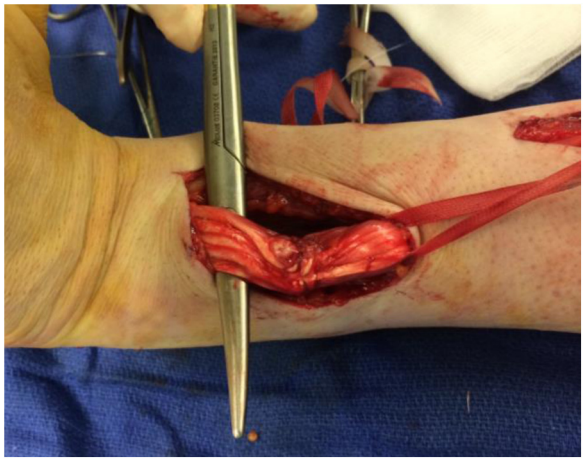

Fig. 3. FCU to EDC tendon transfer: tendon suturing was performed in an end-to-side fashion, proximal to the extensor retinaculum.

Fig. 4. FCR to EDC tendon transfer: the FCR is passed subcutaneously on the radial side of the forearm. On the ulnar side, appearance after PL to EPL transfer with a Pulvertaft weave.

4.3.3. FDS transfer

The FDS must be harvested between the A1 and A2 pulleys and transected proximally to the chiasma at the base of the finger. In fact, harvesting the FDS at its insertion site can cause a flexion contracture secondary to the surgical trauma of the tendon sheath of the donor finger. The harvesting can also be responsible for a swan-neck deformity, especially in patients with joint hypermobility. At the forearm level the incision is anterior. The FDS can be passed around the ulnar or radial side of the wrist, or through the interosseous membrane for a more direct course. The FDS III is passed between the FDP and FPL, while the FDS IV is passed on the ulnar side of the FDP. They are then passed through the interosseous membrane, which has been opened as wide as possible proximally to the pronator quadratus, to allow for easy passage. Tendon suture (FDS III to EPL and EIP + FDS IV to EDC) is generally done proximal to the retinaculum [12]. It can also be done on the dorsum of the hand after having passed the tendons under the extensor retinaculum instead of the extensor tendons [15]. To prevent a flexion deficit, the tension must be set by flexing the patient's fingers and thumb to achieve a closed fist with the wrist held in 20 ° extension. Tendon suturing is done with maximum tension placed on the FDS [12].

4.4. Transfer of PL on EPL

The PL is transected at its distal end and released proximally. One must be aware of the palmar cutaneous branch of the median nerve located laterally to the tendon. The EPL is transected at the

musculotendinous junction. It is removed from its groove distal to the retinaculum and re-routed laterally to Lister's tubercle, subcutaneously, or passed into the first or second compartment (see above). Tendon suturing is done with the wrist in neutral position, the thumb held in extension, retropulsion and radial abduction with the PL under tension.

5. Postoperative care and rehabilitation

Postoperative immobilization places the elbow in 90 ° flexion, forearm pronated to release the transfer of the PT to the ECRB. The wrist is immobilized in 50 ° extension without frontal deviation, the thumb column in extension, retropulsion and abduction, and the finger MCP joints straight. The PIP joints are left free, which allows for early active flexion-extension motions. This immobilization lasts 3 weeks, then is used at night for another 3 weeks. Some surgeons recommend that patients wear a splint between rehabilitation sessions up to the 6th week postoperative.

Passive and active assisted rehabilitation is started on the 22nd day. Up to the 6th week, exercises focus on the mobilization of a single joint: mobilization of the elbow in flexion-extension is done with the wrist and fingers in extension; mobilization of the wrist is done with the fingers extended and the elbow flexed; flexion of the MCP joints is done with the wrist extended and the elbow flexed. Active movements are allowed starting at day 45. No strength work is allowed until the end of the 3rd month postoperative.

6. Results

The results of tendon transfers for radial palsy are generally highly satisfactory.

At 60 months' follow-up, Altintas et al. reported results in 77 patients who underwent a tendon transfer for radial palsy using the FCR for finger extension (19 cases) or the FCU (56 cases). Relative to the contralateral side, the patients had recovered 74% of wrist extension and 32% of finger extension. The DASH score was 15 ± 9 and 89% were able to return to work after the surgery [39]. Ropars et al. reported 13 good or excellent results in 15 tendon transfers after use of the FCR (10), FCU (4) or the ECRL for low radial nerve palsy (1); however, there was loss of grip strength and radial deviation, especially in patients who underwent FCU to EDC transfer [40]. Kruft et al. reported excellent outcomes in 43 patients after a Merle d'Aubigné transfer: 38 patients were able to return to their former job, there was no radial deviation of the wrist when extended, and most patients could move their fingers independently through a controlled action of the flexors [41]. In a comparative study of 41 patients, Moussavi et al. compared the use of the FCR (10), FCU (18) or FDS (13) to restore finger extension. They found no significant difference in the range of motion, DASH score, satisfaction or return to work; the overall satisfaction rate was 95% [42].

7. Nerve transfer

Recently, nerve transfers were described by MacKinnon's team to restore extension of the wrist, fingers, and thumb. In this technique, the FDS nerve is transferred to the ECRB nerve, while the FCR nerve is transferred to the DBRN. Excellent results were reported up to 10 months after the initial radial nerve injury. This nerve transfer has the potential to restore normal radial nerve function while preserving finger independence [43]. In a case series of 19 patients, 18 of them had good or excellent wrist extension. Regarding thumb and finger extension, 12 patients had good or excellent results, 2 fair and 5 poor. Eight of the patients underwent simultaneous transfer of the PT to the ECRB, while another patient later on underwent a FCR to EDC and a PL to EPL tendon transfer. The authors stopped doing proximal radial nerve grafting and instead perform nerve transfers [44]. They continue to do tendon transfers since the outcomes are predictable, faster and do not require prolonged rehabilitation (10–12 months after nerve transfers).

Nerve transfers can also be done to restore extension of the wrist, fingers and thumb in cases of high brachial plexus (C5-C7) or low brachial plexus injury (C7-T1) or injury of the posterior cord of the brachial plexus [45].

The decision to use a nerve transfer versus a tendon transfer is made specifically for each patient. The results are promising, thus additional studies are needed to determine the role of nerve transfer relative to radial nerve grafting or tendon transfers.

8. Conclusion

If the technical rules are followed, tendon transfers for radial nerve palsy routinely provide highly satisfactory results. But one should not forget that this is a palliative solution and that a very good tendon transfer result never equates a very good primary nerve surgery result. If the objectives of wrist and finger extension are met by tendon transfers, limited wrist flexion or limited finger flexion when the wrist is flexed is often the consequence; luckily, the functional impact is limited.

Conflict of interest

The authors have no conflicts of interest to declare.

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