European Journal of Orthopaedic Surgery & Traumatology (2019) 29:521–530
https://doi.org/10.1007/s00590-018-2352-2

GENERAL REVIEW • HAND -EXPERIMENTAL

Combining nerve and tendon transfers in tetraplegia: a proposal of a new surgical strategy based on literature review

Paolo Titolo[1] · Federico Fusini[2] · Chiara Arrigoni[3] · Gianluca Isoardo[5] · Luigi Conforti[2] · Stefano Artiaco[1] · Davide Ciclamini[1] · Monica Sicari[4] · Bruno Battiston[1]

Received: 1 October 2018 / Accepted: 3 December 2018 / Published online: 12 December 2018

Abstract

Spinal cord injury (SCI) is very common, most frequently resulting from motor vehicle accidents and falling from a height. Often, SCI occurs at the cervical level, resulting in tetraplegia, which consists of loss of effective arm and/or hand function. For these patients, hand function is considered the most desired function, above bowel, bladder and sexual function. Fortunately, understanding about nerve and tendon transfers is steadily growing, providing new surgical solutions for functional restoration in tetraplegia patients. The primary aim of this systematic review of the literature is to assess all the various ways to improve upper-limb function, using both nerve transfers and classical tendon transfers in patients suffering from tetraplegia. Surgical indications, optimum timing and contraindications were reviewed. In accordance with the International Classification for Surgery of the Hand in Tetraplegia, ten subgroups of tetraplegic patients were analysed and a proposal for treatment combining nerve and tendon transfers formulated for each subgroup, seeking alternatives to classical surgical strategies. We also sought to propose strategies that, in instances of failure, still would allow for the use of some classical surgical approach. Starting with traditional management, we proposed new strategies using tenodesis and tendon transfers in association with nerve surgery. We believe that the suggestions described in the current paper could both improve and complete current surgical strategies and contribute to ensuring that more patients benefit from these options in future.

Keywords Nerve transfers · Tetraplegic hand · Tendon transfers · Surgical strategy

Introduction

The global incidence of spinal cord injury (SCI) has been estimated at between 10 and 80 new cases per million people annually [1]. The most common causes are motor vehicle accidents and falling from a height; with a higher incidence among males between 16 and 30 years old [2]. More than 50% of all spinal cord injuries occur at the cervical level, resulting in tetraplegia and the resultant loss of effective arm and/or hand function.

For the majority of people with tetraplegia, restored hand function is the most essential desire, above the restoration of bowel, bladder and sexual function, the ability to stand, and pain control [3, 4]. Even partial recovery of arm and hand function can have an enormous impact on a person's independence and quality of life, since patients with cervical spinal cord injuries often are completely dependent upon other people for mobility and the activities of daily living [3, 5, 6]. Tendon transfers restore active control and strength of an anatomical segment, while sacrificing another functional

✉ Federico Fusini
fusinif@hotmail.com

[1] Department of Orthopedics and Traumatology II, Surgery for Hand and Upper Limb, CTO Hospital, AOU Città della Salute e della Scienza di Torino, Turin, Italy

[2] Department of Orthopaedic and Traumatology, CTO Hospital, University of Turin, Via Zuretti 29, 10121 Turin, Italy

[3] Reconstructive Microsurgery and Hand surgery Unit, Istituto Giannina Gaslini, Genoa, Italy

[4] Department of Physical Medicine and Rehabilitation, Spinal Unit, AOU Città della Salute e della Scienza di Torino, Turin, Italy

[5] Department of Neurosurgery, Unit of Clinical Neurophysiology, CTO Hospital, AOU Città della Salute e della Scienza di Torino, Turin, Italy

muscle. The main problem with cervical SCI is that there often is a paucity of adequate donor muscles available for transfer [2].

Nerve transfers involve coapting a healthy, expendable donor nerve or fascicle to a denervated recipient nerve to restore function to the recipient end organ (i.e. to the skin to restore sensation or to a muscle to restore motor function) [7]. However, nerve transfers also often sacrifice potentially useful neural structures. The aim of the current literature review is to resume the present surgical indication and suggest a way to improve upper-limb function, in patients with tetraplegia, using both nerve transfers and conventional tendon transfers.

A research was constructed using the MEDLINE database via PubMed and Scopus. Articles published in English, Italian and French, up to the 30th of June 2018, were found using the following keywords alone or in combination: tetraplegia, tendon transfer, tenodesis, nerve transfer, upper limb and spinal cord injury. Articles were eligible if they provide specific information related to the correlation between nerve and tendon transfers in tetraplegia. Articles retrieved were used to assess classification, indications, timing of surgery and choices of treatment based on the International Classification for Surgery of the Hand in Tetraplegia (ICSHT).

Classifications

ICSHT organizes the most common patterns of upper-limb lesion in tetraplegics by the number of muscles that remain functional below the elbow. A muscle is defined as functional if its strength is graded 4 or more, using the muscle grading system approved by the British Medical Research Council (BMRC) [8] (Table 1). The ICSHT guides surgeons in their choice of reconstructive strategies (primarily emphasizing tendon transfer and tenodesis procedures) (Table 2). The surgical strategy generally utilizes tendon transfers, tenodesis and arthrodesis, with many authors proposing a combination of these techniques, with predictable results [2]. However, attention must be paid to the risks associated with sacrificing a donor muscle, so that another problematic functional deficit arises following the tendon transfer.

Donor muscles are prioritized to achieve wrist extension recovery first, then pinch strength, grasp strength, finger and thumb extension and, finally, intrinsic muscle function [7, 9]. When no further muscle transfer options exist, the remaining desirable functions generally are restored using tenodesis and arthrodesis [2].

Nerve transfer techniques are commonly used to restore motor function in the setting of brachial plexus nerve root avulsion injuries, for which anatomical repair of the native motor nerve is impossible. They are also useful with other peripheral nerve injuries, where rapid restoration of function can be accomplished by rerouting expendable donor nerves. Over the last few years, some authors have introduced the use of nerve transfers for tetraplegia, reporting unexpected results.

Following these concepts, we propose a new strategy, based upon classical tendon surgery, but adding nerve transfer techniques (Table 3). This combination addresses frequent concerns about nerve transfers that using sources with "predictable" results (i.e. the muscle–tendon unit innervated by the nerve that will be used as a donor) to achieve "unpredictable" results. In fact, using selected donor nerve transfers which avoid sacrificing useful muscles allows for second-stage surgeries to follow classical tendon transfer and tenodesis techniques.

Table 1 International Classification for Surgery of the Hand in Tetraplegia (ICSHT)

Motor group	Characteristics	Function
0	No muscle below elbow suitable for transfer	
1	BR	Flexion and supination of the elbow
2	ECRL	Extension of the wrist
3	ECRB	Extension of the wrist
4	PT	Pronation of the wrist
5	FCR	Flexion of the wrist
6	Finger extensors	Extrinsic extension of the fingers
7	Thumb extensor	Extrinsic extension of the thumb
8	Partial digital flexors	Extrinsic flexion of the fingers
9	Lacks only intrinsics	
10	Exceptions	

BR brachioradialis, *ECRL* extensor carpi radialis longus, *ECRB* extensor carpi radialis brevis, *PT* pronator teres, *FCR* flexor carpi radialis

Table 2 Muscle grading system of the British Medical Research Council, muscle function ranged from 0 (no contraction) to 5 (normal power)

Groups	Description
0	No contraction
1	Flicker or trace of contraction
2	Active movement with gravity eliminated
3	Active movement against gravity
4	Active movement against gravity and resistance
5	Normal power

Table 3 Combining nerve and tendon strategy in tetraplegia

ICS group	Primary procedures		Positive outcome?		Secondary procedures
0	Teres minor to triceps nerve transfer	→	NO	→	Posterior deltoid to triceps tendon transfer
	Brachialis to ECRL nerve transfer	→	YES	→	Flexor pollicis longus tenodesis + Moberg key-pinch procedure
1 (BR $\geq$ M 4)	Teres minor to triceps nerve transfer	→	NO	→	Posterior deltoid to triceps tendon transfer
	Brachialis to AIN/FDS nerve transfer	→	YES	→	Extensor digitorum communis tenodesis + Extensor pollicis longus tenodesis
			NO	→	Flexor pollicis longus tenodesis + Moberg key-pinch procedure
	BR to ECRB tendon transfer				
2 (ERCL $\geq$ M 4)	Teres minor to triceps nerve transfer	→	NO	→	Posterior deltoid to triceps tendon transfer
	Supinator to PIN nerve transfer	→	NO	→	Extensor digitorum communis tenodesis + Extensor pollicis longus tenodesis
	Brachialis to AIN/FDS nerve transfer	→	YES	→	BR to opposition
			NO	→	BR to FPL tendon transfer
3 (ERCB $\geq$ M 4)	Teres minor to triceps nerve transfer	→	NO	→	Posterior deltoid to triceps tendon transfer
	Supinator to PIN nerve transfer	→	NO	→	Extensor digitorum communis tenodesis + Extensor pollicis longus tenodesis
	Brachialis to AIN/FDS nerve transfer	→	YES	→	BR to opposition
			NO	→	BR to FPL tendon transfer + Tenodesis FDP 2° to FDP 3°–4°–5°
	ECRL to FDP (3°–4°–5° finger) tendon transfer				
4 (PT $\geq$ M 4)	Supinator to PIN nerve transfer	→	NO	→	Extensor digitorum communis tenodesis + Extensor pollicis longus tenodesis
	Brachialis to AIN/FDS nerve transfer	→	YES	→	BR to opposition
			NO	→	BR to FPL tendon transfer + Tenodesis FDP 2° to FDP 3°–4°–5°
5 (FRC $\geq$ M 4)	ECRL to FDP (3°–4°–5° finger) tendon transfer				
6 (EDC $\geq$ M 4)	EPL tenodesis				
	Brachialis to AIN/FDS nerve transfer	→	YES	→	BR to opposition
			NO	→	BR to FPL tendon transfer + Tenodesis FDP 2° to FDP 3°–4°–5°
	ECRL to FDP (3°–4°–5° finger) tendon transfer				
7 (EPL $\geq$ M 4)	Brachialis to AIN/FDS nerve transfer	→	YES	→	EDM to APB or EIP to APB
			NO	→	BR to FPL tendon transfer + Tenodesis FDP 2° to FDP 3°–4°–5° + EDM to APB or EIP to APB
	ECRL to FDP (3°–4°–5° finger) tendon transfer				
8 (partial finger flexion)	ECRB to AIN nerve transfer	→	YES	→	EPI/EDM to opposition
			NO	→	BR to FPL tendon transfer + Tenodesis FDP 2° to FDP 3°–4°–5° + EPI/EDM to opposition
9 (Intrinsic deficit)	Intrinsic reconstruction (Zancolli lasso/House intrinsic procedure)				
	Opponensplasty				

A new proposal of surgical treatment based on ICSHT group. In case of failure of the proposed treatment, a salvage procedure (conventional treatment) is always possible

Indications

The indications for this new surgical strategy include any cervical spine injury that leads to partial paralysis of one or both upper limbs, but patients also must have stabilizing motor function in the affected upper extremity. They must be medically stable, free of infections and, ideally, free of contractures, pain and spasticity. In addition, they must exhibit full passive range of motion and be motivated to follow whatever post-operative rehabilitation regimen that they are prescribed [2]. Before surgery, patients must understand the difference between the classic and new treatment strategies, in terms of recovery time, since noticeable results often take considerably longer to appear following nerve transfers than muscle or tendon procedures, and a second-stage procedure is often necessary to achieve the desired level of functional restoration. Having a patient with realistic expectations plus strong motivation to improve their hand function is essential to obtaining good results [10]. Contraindications to surgery are the presence of spasticity or contractures, and chronic pain problems, but also, psychological instability, unrealistic expectations or insufficient motivation, all of which generally lead to poor outcomes [11].

Timing of surgery

The timing of nerve transfers for tetraplegia is still debated. Fox [12] described two basic time schedules for intervention: time independent and time dependent. If there is a clear-cut SCI with a narrow zone of anterior horn cell damage, a peripheral nerve transfer can reconnect functional motor units to the brain to restore muscle movement. This transfer switches motor control from a redundant and expendable donor to a muscle group distal to the lesion site, bypassing the level of injury. Ideally, this can be done at any time after the SCI, because neuromuscular degeneration is very slow.

If, on the other hand, the zone of injury is more extensive, roots can be involved with a peripheral nerve lesion and a time-dependent rescue strategy must be adopted (Fig. 1). Nerve donors should be used to restore voluntary control or reinnervate muscles that would otherwise atrophy [13]. Despite these considerations, denervated muscles should benefit from early surgery, before the onset of muscular atrophy, while paralysed muscles leave more time for surgery, due to a diminished neuromuscular degeneration rate, leading to time-dependent results in tetraplegics [14]. Traditionally, it is recommended that tendon transfers are performed 1 year after the injury since, by then, all possible spontaneous neurological recovery has already occurred. However, most neurological recovery generally occurs within the first 6 months following an injury [11]. Moreover, it is generally accepted that, after 1 year of denervation, terminal muscle atrophy may prevent the restoration of function [15, 16].

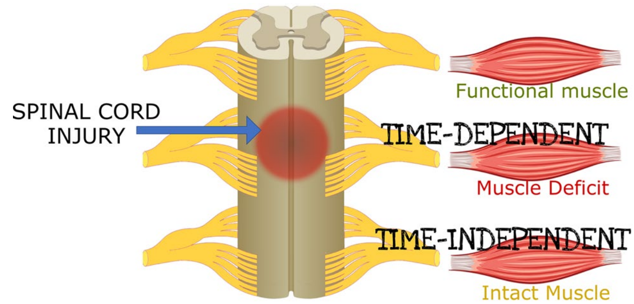

Fig. 1 Time-dependent and time-independent nerve transfer based on spinal cord injury level. Over the lesion, the muscle is functional. At the level of injury, the muscle is not directly innervated by spinal cord and function restoration is time dependent. Under the level of injury, the muscle is still innervated by spinal cord. The function restoration is time independent

Addressing these concepts, Lamb and Chan observed that, if a muscle is completely paralysed during the initial assessment and is unchanged 1 month later, it is unlikely that there will be any significant recovery, even waiting 1 year [17]. On the other hand, Bertelli et al. [18] reported distal nerve transfers performed 18 months after spinal cord injuries that generated functional muscle reinnervation. Based upon these observations, it may be that the ideal time for surgery is between 6 and 12 months after the trauma, before the onset of irreversible muscle atrophy. Earlier procedures should be considered only if electromyography (EMG) demonstrates muscle denervation, resulting from neuronal death at the site of the SCI [19]. To allow better understanding of our reconstructive strategies, we describe, for each ICSHT classification group, both primary and secondary procedures (Table 3).

Group 0

Since these lesions are at C5 or an even higher level, no muscles with grade 4 strength or better exist below the elbow. In one larger series, ICSHT groups 0 and 1 were lumped together, in which case they represented almost 30% of lesions [13].

We have proposed employing a teres minor to triceps nerve transfer, and a brachialis to extensor carpi radialis longus nerve transfer. In this patient group, elbow extension should be restored, which can be done with tendon transfers (Moberg's procedure, involving a posterior deltoid to triceps transfer, or Zancolli's procedure, involving a biceps-to-triceps transfer) [20–22] or with nerve transfers. Performing a teres minor motor branch to the triceps long head motor branch transfer [19] allows for marked recovery of elbow extension without any donor-site deficits, because the infraspinatus muscle compensates for any external rotation deficit that follows from sacrificing teres minor innervation. Furthermore, the teres minor is not usually transferred in tetraplegia, and its sacrifice does not prevent Moberg's procedure from being undertaken later to improve upon partial recovery or as a second-stage surgery in cases of failure.

Bertelli and Ghisoni [18] also described utilizing the posterior division of the axillary nerve to the triceps long and medial head nerve. We prefer using the teres minor motor branch; this is because, if the procedure fails, a second-stage surgery, transferring the posterior deltoid tendon to the triceps, can still be performed (Moberg's procedure).

In this patient group, the shoulder must be thoroughly evaluated, in case there is partial deficit of deltoid and teres major muscle function, so that no surgical strategy further weakening the deltoid is employed to restore elbow extension.

Conventional surgical wisdom considers any tendon transfers to restore wrist or hand function useless in these group 0 patients. Restoring wrist extension is really important, because tenodesis may enable thumb-to-index key pinch, driven by wrist motion, increasing the patient's autonomy and restoring some critical abilities, like eating, personal care and wheelchair propulsion. Fridén and Gohritz introduced the brachialis to extensor carpi radialis longus (ECRL) selective nerve transfer to restore wrist extension in group 0 tetraplegics [23]. The brachialis muscle is primarily innervated by a single branch of the musculocutaneous nerve, derived from spinal roots C5 and 6. This branch can be used as a donor if the biceps is functional. Of course, this would circumvent employing a secondary Zancolli's procedure—a biceps-to-triceps transfer—to restore elbow extension. If the brachialis to ECRL transfer succeeds, group 0 patients have effectively been transformed into group 1 patients, and secondary procedures like flexor pollicis longus tenodesis and Moberg's passive key-pinch reconstruction become possible [2].

Group 1

In group 1 patients, the offending lesion is at the C5 level. In this group, only the brachioradialis muscle has grade 4 strength or better; all the other muscles below the elbow have less than grade 4 strength. In these patients, elbow flexion is preserved because the biceps and brachialis are innervated above this level.

We propose performing a teres minor to triceps nerve transfer; brachialis to anterior interosseous nerve (AIN) and flexor digitorum superficialis (FDS) nerve transfers; and a brachioradialis (BR) to extensor carpi radialis brevis (ECRB) tendon transfer. The classic strategy proposes two procedures that can be performed simultaneously: a brachioradialis to extensor carpi radialis brevis tendon transfer (BR to ECRB) to restore active wrist extension, and passive key-pinch reconstruction based on flexor pollicis longus (FLP) tenodesis, with or without additional "tricks" proposed by Hentz [24], Johanson [25] and House [26]. As in the previous group, elbow extension can be restored with Moberg's or Zancolli's procedure. Transferring the brachioradialis tendon to radial wrist extensors is a reliable technique that may provide sufficient strength to extend the wrist against resistance [18, 19].

Mackinnon et al. [27] described transferring the brachialis to the anterior interosseous nerve in patients with SCI. This technique offers the option of improving intrinsic hand function, a crucial component of pinching; it may also enhance the patient's hand function and ability to feed him- or herself [28]. Fox et al. [13, 29, 30] described their results using brachialis to AIN and FSD nerve transfers. Any degree of flexor pollicis longus function, even subtle, will improve the tenodesis-effect grasp and some strength and holding power [30]. If the brachialis to AIN/FDS generates a good result and pinch function is restored, function can be further enhanced via a second-stage procedure that consists of ECD and EPL tenodesis. With this, hand opening and grasp function are improved. If the procedure fails, a second-stage surgery involving FLP tenodesis can still be performed.

Group 2

As with group 3, the lesion in group 2 patients is at the C6 level. However, it is difficult to discriminate between the ECRL (group 2) and ECRB (group 3) based on differential strength. In group 2 patients, the BR and ECRL should have at least grade 4 strength. Different methods are described to help in this discrimination, but none seems to be really effective. Mohammed and colleagues described Bean's sign [31]; Moberg suggested surgical exploration [22, 24]; Allieu [32] used the pronator teres to indicate function in the two extensors; and so on. This is important, because Hentz et al. [24] suggested ECRL transfers only if the ECRB is of grade 5, and not grade 4, strength.

To give a more precise description of the new strategy, we try to consider these two groups (2 and 3) separately. As such, the main aim of nerve transfers in this group is to restore a more effective pinch and permit active, functional finger extension and flexion. The strategy we consider most promising involves a teres minor to triceps nerve transfer; supinator to posterior interosseus nerve (PIN) transfer; and brachialis to anterior interosseous nerve (AIN) and flexor digitorum superficialis (FDS) nerve transfers. The current approach emphasizes restoring key-grip thumb function. This objective is achieved using House's one-stage active key-pinch reconstruction, which adds a BR to FLP tendon transfer to Henz's procedures (FLP split, fixation of the IP with a K wire, or arthrodesis of the IP joint of the thumb), and CMC fusion and EPL tenodesis to balance the tendency towards flexion [33].

As with the previous two groups, elbow extension must be restored. We propose a strategy that incorporates a teres minor to triceps nerve transfer; supinator to a PIN nerve transfer; and brachialis to AIN and FDS nerve transfer. Supinator motor branches start from the PIN, which is the distal motor division of the radial nerve in the forearm.

In patients with a C6 lesion, not all the muscles innervated by the radial nerve are lost. The supinator is one of these, because it is also innervated by neurons located above the lesion and could be used to improve finger and thumb extension. Bertelli et al. [34] have claimed that, in the presence of strong wrist extensors, the supinator muscle is always functional. Supination is preserved by a functional biceps [18]. Nerve transfer to the PIN should allow for reinnervation, not only of the ECD and extensor pollicis longus, but also of the abductor pollicis longus and extensor pollicis brevis (avoiding trapezio-metacarpal joint arthrodesis or abductor pollicis longus tenodesis), and reinnervation of the extensor carpi ulnaris, which could eventually be transferred secondarily to the flexor carpi ulnaris to stabilize the wrist when the digits are extended [34]. Bertelli and Ghizoni [35] also proposed free gracilis muscle transfers for thumb and finger extension, with innervation supplied by the supinator in patients with long-standing tetraplegia, when electrical stimulation of the PIN fails to produce muscle contraction.

If transferring the teres minor motor branch to the triceps long head motor branch fails, a second-stage surgery involving a posterior deltoid tendon transfer to the triceps can be performed (Moberg's procedure). If transferring motor branches for the supinator to the PIN fails, a second-stage surgery involving ECD and EPL tenodesis remains an option. If transferring the motor nerve branch to the brachialis to the AIN produces a good result, it can eventually be followed by a BR tendon transfer, employing a tendon graft to improve thumb opposition [26]. In cases of failure, the conventional approach can still be performed, consisting of House's one-stage active key-pinch reconstruction: adding a BR to FLP tendon transfer to Henz's procedures (FLP split, fixation of IP with a K wire or an arthrodesis of the IP joint of the thumb), as well as CMC fusion and EPL tenodesis to balance the tendency towards flexion.

Group 3

As with group 2, in group 3 patients, the lesion is at the C6 level. This group differs from the previous one, in that both the ECRL and ECRB exhibit grade 4 or more strength. Current strategies involve a teres minor to triceps nerve transfer; a supinator to PIN nerve transfer; a brachialis to AIN and FDS nerve transfer; and ECRL to FDP (3rd to 5th finger) tendon transfers. This conventional strategy stems from Zancolli's procedure [31]. He divided reconstruction into two steps: a first stage, aiming to restore extension functions, and a second stage to restore flexion functions. For the first stage (restoring extension), he suggests an extensor tenodesis (ECD and EPL tenodesis); a "lasso procedure"; and thumb IP joint fusion. Zancolli's "lasso procedure" goal is to prevent MP joint hyperextension or clawing of the fingers during extension; it uses the FDS to flex the MP joints [2]. For his second stage (restoring flexion), he suggests an ECRL to FDP tendon transfer; and a BR to FLP tendon transfer. This step must be done after scar resolution and functional tenodesis have been achieved from the first step.

Some surgeons prefer to treat group 3 patients like their group 2 counterparts, employing House's one-stage active key-pinch reconstruction to avoid the loss of wrist strength. We propose a strategy that incorporates a teres minor to triceps nerve transfer; a supinator to PIN nerve transfer; a brachialis to AIN and FDS nerve transfer; and an ECRL tendon transfer to the third through fifth finger FDPs.

If the teres minor motor branch to the triceps long head nerve transfer fails, a second-stage procedure that involves transferring the posterior deltoid tendon to the triceps can be performed (Moberg's procedure). If transferring the PIN fails to restore thumb and finger extension, a second-stage procedure can be undertaken that consists of ECD and EPL tenodesis.

Bertelli suggests using ECRB to AIN nerve transfers and, in cases of nerve transfer failure, a secondary procedure involving a brachialis (with graft) and brachioradialis tendon transfer to enhance finger flexion [36]. Bertelli and Ghizoni [37] recently observed flexion recovery in all fingers after transferring the ECRB to the AIN, probably due to intermuscular nerve connections between the ulnar and AIN branches; they concluded that utilizing the ECRB as a donor to the AIN produced better recovery of finger flexion than using the brachialis or brachioradialis as a donor.

Brachialis to AIN nerve transfers remain our first choice, as we prefer to spare the ERCB for secondary tendon transfers. In our hands, ECRB tendon transfers restore finger flexion very reliably. The eventual preponderance of finger flexion generated by tendon transfers, during the phase of inadequate recovery of extension (because of the supinator to PIN nerve transfer), can be managed with the support of a dynamic radial nerve palsy splint, until extension function recovers or until some secondary surgery (extensor tenodesis) is performed when the nerve transfer fails. We suggest not primarily transferring the ECRL to the FDP for the index finger because, if the brachialis to AIN nerve transfer has a good result, active and independent index finger pinch function may be restored. If transferring the motor nerve branch to the brachialis to the AIN produces a good result, restoration can be completed with a BR transfer to improve thumb opposition [26]. On the other hand, in cases of brachialis to AIN nerve transfer failure, tenodesis of the index FDP to the FDPs of the other fingers (3–5), controlled by concomitantly performing an ECRB tendon transfer and a BR to FLP tendon transfer, could be performed. Eventually, additional procedures, depending upon the extent of secondary recovery (e.g. FLP split, fixation of the IP with a K wire, arthrodesis of the IP joint of the thumb, CMC fusion) could be considered.

Group 4

Patients in this group also have their lesion at the C6 level, but grade 4 or greater strength in the pronator teres, which can then be considered for transfer, paying attention to its important role in manual wheelchair propulsion. The optimal strategy involves a supinator to PIN nerve transfer; a brachialis to the AIN and FDS nerve transfer; and ECRL to FDP tendon transfers for digits 3–5.

In this group, more muscles are available for tendon transfer (BR, ECRL, PT) and the ECRB is generally preserved to maintain good wrist control [2]. For this reason, the conventional strategy consists of two-stage reconstruction of grasp and release movements, in accordance with House's strategy. The first, extensor phase consists of three surgical steps: carpometacarpal (CMC) fusion and ELP tenodesis; extensor digitorum communis tenodesis to the distal radius (or a BR to ECD transfer); and an intrinsic tenodesis using a free tendon graft routed through the lumbrical canals [26]. The second, flexion phase consists of two or more surgical steps: a BR or PT transfer to the FLP; an ECRL to FDP transfer; and, perhaps eventually, generating BR or PT opposition with an FDS graft. If the PT is used as a transferred tendon for the FLP, the BR could be considered to restore adduction-opponens function, if it is transferred using a paralysed FDS; this can be considered an "in situ tendon graft" [2].

Another possible strategy is similar to the one previously described for group 3, with some differences. Transferring the teres minor to the triceps is unnecessary because, with lesions at this level, the triceps is quite functional. Another surgical step could be a PT to FSD nerve transfer. Garcia-Lopez et al. [38] have claimed that two branches of the median nerve innervate the PT and that transferring one of these branches to the ECRL resulted in restoration of M4 wrist extension in six patients with a high radial nerve palsy, while preserving at least M4 pronation strength. On the other hand, with a radial nerve palsy, pronation can still be accomplished with the pronator quadratus, and with the flexor carpi radialis and flexor digitorum profundus and superficialis. As such, it is difficult to predict the real pronation deficit that results from Garcia-Lopez and colleagues' procedure in group 4 tetraplegics.

In a normal hand, pronation from full supination to neutral is probably also achieved with the brachioradialis, with contributions from the extensor carpi ulnaris and extensor digiti minimi [37, 39]. In group 4 patients, only the brachioradialis will induce partial pronation, in patients with a PT deficit. Furthermore, the PT provides considerable power for manual wheelchair propulsion. Consequently, we suggest avoiding PT to FSD nerve transfers. For a secondary procedure, one option is adding House's intrinsic muscle procedure.

Group 5

In this group, the lesion is at the C7 level and patients have FRC strength equal to grade 4 or 5. One potential strategy involves a supinator to PIN nerve transfer; a brachialis to AIN and FDS nerve transfer; and ECRL to FDP tendon transfers for the third through fifth fingers. The current operative strategy is the same as for group 4. Moreover, we propose the same approach for group 4 that other authors have already endorsed. It is possible to use the FCR as a nerve transfer to either the PIN [38] or AIN. However, we agree with House's suggestion that the FCR be kept in place, to preserve maximal wrist control [33].

Group 6

Among patients in this group, the lesion is at the C7 level and patients have EDC strength measuring 4 or greater. Consequently, the extensor stage of reconstruction is unnecessary; only flexors must be restored. These patients have a "flat-hand" appearance, because they have unopposed digital extension and lack an active grasp. They have strong shoulder and elbow control, with excellent ability to position their hand in space. For this reason, they benefit from grasp and pinch reconstructive surgery.

The optimal surgical strategy should involve EPL tenodesis; a brachialis to AIN and FDS nerve transfer; and ECRL to FDP tendon transfers for the third through fifth fingers.

Active finger extension is strong, but EPL function is absent or weak. For this reason, EPL tenodesis or transfer onto the EDC can be done to improve thumb extension. The conventional strategy adds to this; the same flexion-phase procedures suggested for the previous two patient groups.

Our strategy consists of EPL tenodesis; ECRL tendon transfers to the third through fifth finger FDPs; and a brachialis to AIN/FDS nerve transfer. Bertelli and others propose transferring the distal terminal motor branch of the extensor carpi radialis brevis to the nerve of the flexor pollicis longus to reconstruct thumb flexion, and a brachialis tendon transfer with a graft to restore finger flexion [40–43]. As previously stated, we prefer to avoid any ECRL nerve transfers, instead employing tendon transfers to reanimate finger flexion. For a secondary procedure, adding House's intrinsic muscle procedure is, once again, an option.

Group 7

In this group, the lesion is again at the C7 level, but even the EPL has level 4 strength or greater. Both finger and thumb extensors are strong, so only flexor recovery is needed. The conventional strategy consists of ECRL transfer to the FDP, and BR or PT transfers to the FLP to restore an active pinch (as in the previous groups). One feasible strategy involves a brachialis to AIN and FDS nerve transfer and ECRL to FDP tendon transfers, again for digits 3–5. Adding to these procedures, thumb control can be improved with CMC fusion and an opponensplasty, depending on the thumb's stability and patient's preference. Intrinsic reconstruction can also be performed to improve digital grasp (the Lasso procedure) [44]. We propose adopting the same approach as described for group 6, without EPL tenodesis. As a secondary procedure, we prefer adding an extensor indicis proprius (EIP) or extensor digiti minimi (EDM) opponensplasty and, eventually, intrinsic reconstruction procedures, as suggested by both Zancolli [41] and Bourrel [43].

Group 8

Among group 8 patients, the offending lesion is at the C8 level, and patients have an intact FUC and partial FDP function. Usually, the flexors of the two most ulnar-side fingers are stronger than those of the thumb, index and middle fingers.

The conventional strategy to improve finger flexion consists of Zancolli's two-stage reconstruction, entailing extrinsic transfers and intrinsic reconstruction. Extrinsic transfers consist of side-to-side sutures of the four profundus tendons, while half of the index FDP is woven transversely across the other tendons to ensure the right tension. Another step is a BR or PT to FPL transfer. And a further option is an ECRB to second FP tendon transfer to achieve independent flexion of the index finger.

We propose transferring a nerve branch to the ECRB to the AIN [32, 33]. If this procedure fails, it is nonetheless still possible to use House's one-stage active key-pinch reconstruction (BR to FLP tendon transfer) followed by Henz's procedures (FLP split, fixation of IP with a K wire, or arthrodesis of the IP joint of the thumb). CMC fusion and EPL tenodesis will balance tendencies towards flexion, while tenodesis of the second FDP to the third, fourth and fifth finger FDPs will complete hand function. Reconstruction of intrinsic muscle function consists of an opponensplasty with the EPI or EDM, a Zancolli lasso technique, and CMC fusion or intrinsic tenodesis (House's technique) [26]. Opponensplasty and intrinsic function reconstruction may be considered secondary procedures.

Group 9

Patients in group 9 have functioning FDS muscles, as well as all the other extrinsic finger and thumb flexors and extensors, but they lack intrinsic muscle innervation. These patients benefit most from opponensplasty and intrinsic reconstructions, depending on the level of intrinsic imbalance present. Clawing of the digits with MP hyperextension of the fingers can be treated with Zancolli's [41] passive or active lasso procedure [44]. PIP flexion deformities due to a central slip deficiency can be treated with House's intrinsic tenodesis.

Conclusions

Starting from conventional treatments, we have proposed new strategies using tenodesis and tendon transfers, in association with nerve surgery, to improve upper-limb function in patients with tetraplegia. The combination of nerve and tendon transfer should be a valuable tool in the hand of surgeons; despite the risk of loss of function and treatment failure, a salvage conventional procedure can always be performed.

Compliance with ethical standards

Conflict of interest All authors declare they have no conflict of interest regarding the topic of this publication.

References

1. Kumar N, Osman A, Chowdhury JR (2017) Traumatic spinal cord injuries. J Clin Orthop Trauma 8:116–124. https://doi.org/10.1016/j.jcot.2017.06.022

2. Wolfe SW, Pederson WC, Hotchkiss RN, Kozin SH, Cohen MS (2010) Green's operative hand surgery: the pediatric hand e-book. Elsevier Health Sciences
3. Anderson KD (2004) Targeting recovery: priorities of the spinal cord-injured population. J Neurotrauma 21:1371–1383. https://doi.org/10.1089/neu.2004.21.1371
4. Brown J (2011) Nerve transfers in tetraplegia I: background and technique. Surg Neurol Int 2:121. https://doi.org/10.4103/2152-7806.84392
5. Waters RL, Sie IH, Gellman H, Tognella M (1996) Functional hand surgery following tetraplegia. Arch Phys Med Rehabil 77:86–94
6. Bednar MS, Woodside JC (2018) Management of upper extremities in tetraplegia. J Am Acad Orthop Surg 26:e333–e341. https://doi.org/10.5435/JAAOS-D-15-00465
7. Limthongthang R, Bachoura A, Songcharoen P, Osterman AL (2013) Adult brachial plexus injury. Orthop Clin North Am 44:591–603. https://doi.org/10.1016/j.ocl.2013.06.011
8. James MA (2007) Use of the Medical Research Council muscle strength grading system in the upper extremity. J Hand Surg 32(2):154–156
9. Zlotolow DA (2011) The role of the upper extremity surgeon in the management of tetraplegia. J Hand Surg Am 36:929–935. https://doi.org/10.1016/j.jhsa.2011.03.001
10. Gohritz A, Fridén J, Herold C, Aust M, Spies M, Vogt PM (2007) Ersatzoperationen bei Ausfall motorischer Funktionen an der Hand. Unfallchirurg 110:759–776. https://doi.org/10.1007/s00113-007-1322-7
11. Lee SK, Wolfe SW (2012) Nerve transfers for the upper extremity: new horizons in nerve reconstruction. J Am Acad Orthop Surg 20:506–517. https://doi.org/10.5435/JAAOS-20-08-506
12. Fox IK (2016) Nerve transfers in tetraplegia. Hand Clin 32:227–242. https://doi.org/10.1016/j.hcl.2015.12.013
13. Fox IK, Novak CB, Krauss EM, Hoben GM, Zaidman C, Ruvinskaya R, Juknis N, Winter AC, Mackinnon SE (2018) The use of nerve transfers to restore upper extremity function in cervical spinal cord injury. PM&R. https://doi.org/10.1016/j.pmrj.2018.03.013
14. Cain S, Gohritz A, Fridén J, van Zyl N (2015) Review of upper extremity nerve transfer in cervical spinal cord injury. J Brachial Plex Peripher Nerve Inj 10:e34–e42. https://doi.org/10.1055/s-0035-1558427
15. Fu SY, Gordon T (1995) Contributing factors to poor functional recovery after delayed nerve repair: prolonged denervation. J Neurosci 15:3886–3895
16. Fu SY, Gordon T (1995) Contributing factors to poor functional recovery after delayed nerve repair: prolonged axotomy. J Neurosci 15:3876–3885
17. Lamb DW, Chan KM (1983) Surgical reconstruction of the upper limb in traumatic tetraplegia. A review of 41 patients. J Bone Joint Surg Br 65:291–298
18. Bertelli JA, Ghizoni MF (2013) Single-stage surgery combining nerve and tendon transfers for bilateral upper limb reconstruction in a tetraplegic patient: case report. J Hand Surg Am 38:1366–1369. https://doi.org/10.1016/j.jhsa.2013.03.056
19. Bertelli JA, Ghizoni MF, Tacca CP (2011) Transfer of the teres minor motor branch for triceps reinnervation in tetraplegia. J Neurosurg 114:1457–1460. https://doi.org/10.3171/2010.12.JNS101519
20. Arnet U, Muzykewicz DA, Fridén J, Lieber RL (2013) Intrinsic hand muscle function, part 1: creating a functional grasp. J Hand Surg Am 38:2093–2099. https://doi.org/10.1016/j.jhsa.2013.08.099
21. Muzykewicz DA, Arnet U, Lieber RL, Fridén J (2013) Intrinsic hand muscle function, part 2: kinematic comparison of 2 reconstructive procedures. J Hand Surg Am 38:2100–2105.e1. https://doi.org/10.1016/j.jhsa.2013.08.098
22. Moberg E (1990) Surgical rehabilitation of the upper limb in tetraplegia. Spinal Cord 28:330–334. https://doi.org/10.1038/sc.1990.43
23. Fridén J, Gohritz A (2012) Brachialis-to-extensor carpi radialis longus selective nerve transfer to restore wrist extension in tetraplegia: case report. J Hand Surg Am 37:1606–1608. https://doi.org/10.1016/j.jhsa.2012.05.005
24. Hentz VR, House J, McDowell C, Moberg E (1992) Rehabilitation and surgical reconstruction of the upper limb in tetraplegia: an update. J Hand Surg Am 17:964–967
25. Johanson ME (2016) Rehabilitation after surgical reconstruction to restore function to the upper limb in tetraplegia: a changing landscape. Arch Phys Med Rehabil 97:S71–S74. https://doi.org/10.1016/j.apmr.2016.03.015
26. House JH, Gwathmey FW, Lundsgaard DK (1976) Restoration of strong grasp and lateral pinch in tetraplegia due to cervical spinal cord injury. J Hand Surg Am 1:152–159
27. Mackinnon SE, Yee A, Ray WZ (2012) Nerve transfers for the restoration of hand function after spinal cord injury. J Neurosurg 117:176–185. https://doi.org/10.3171/2012.3.JNS12328
28. van Zyl N, Hahn JB, Cooper CA, Weymouth MD, Flood SJ, Galea MP (2014) Upper limb reinnervation in C6 tetraplegia using a triple nerve transfer: case report. J Hand Surg Am 39:1779–1783. https://doi.org/10.1016/j.jhsa.2014.06.017
29. Fox IK, Davidge KM, Novak CB, Hoben G, Kahn LC, Juknis N, Ruvinskaya R, Mackinnon SE (2015) Use of peripheral nerve transfers in tetraplegia: evaluation of feasibility and morbidity. Hand (N Y) 10:60–67. https://doi.org/10.1007/s11552-014-9677-z
30. Fox IK, Davidge KM, Novak CB, Hoben G, Kahn LC, Juknis N, Ruvinskaya R, Mackinnon SE (2015) Nerve transfers to restore upper extremity function in cervical spinal cord injury: update and preliminary outcomes. Plast Reconstr Surg 136:780–792. https://doi.org/10.1097/PRS.0000000000001641
31. Mohammed KD, Rothwell AG, Sinclair SW, Willems SM, Bean AR (1992) Upper-limb surgery for tetraplegia. J Bone Joint Surg Br 74:873–879
32. Allieu Y (2002) General indications for functional surgery of the hand in tetraplegic patients. Hand Clin 18:413–421
33. House JH, Comadoll J, Dahl AL (1992) One-stage key pinch and release with thumb carpal-metacarpal fusion in tetraplegia. J Hand Surg Am 17:530–538
34. Bertelli JA, Tacca CP, Ghizoni MF, Kechele PR, Santos MA (2010) Transfer of supinator motor branches to the posterior interosseous nerve to reconstruct thumb and finger extension in tetraplegia: case report. J Hand Surg Am 35:1647–1651. https://doi.org/10.1016/j.jhsa.2010.07.012
35. Bertelli JA, Ghizoni MF (2016) Nerve and free gracilis muscle transfers for thumb and finger extension reconstruction in long-standing tetraplegia. J Hand Surg Am 41:e411–e416. https://doi.org/10.1016/j.jhsa.2016.08.003
36. Bertelli JA (2015) Transfer of the radial nerve branch to the extensor carpi radialis brevis to the anterior interosseous nerve to reconstruct thumb and finger flexion. J Hand Surg Am 40:323–328.e2. https://doi.org/10.1016/j.jhsa.2014.10.060
37. Bertelli JA, Ghizoni MF (2017) Nerve transfers for restoration of finger flexion in patients with tetraplegia. J Neurosurg Spine 26:55–61. https://doi.org/10.3171/2016.5.SPINE151544
38. García-López A, Navarro R, Martinez F, Rojas A (2014) Nerve transfers from branches to the flexor carpi radialis and pronator teres to reconstruct the radial nerve. J Hand Surg Am 39:50–56. https://doi.org/10.1016/j.jhsa.2013.10.011
39. Bertelli JA, Ghizoni MF, Tacca CP (2016) Results of wrist extension reconstruction in C5-8 brachial plexus palsy by transferring the pronator quadratus motor branch to the extensor carpi

radialis brevis muscle. J Neurosurg 124:1442–1449. https://doi.org/10.3171/2015.3.JNS142428
40. Bertelli JA, Mendes Lehm VL, Tacca CP, Winkelmann Duarte EC, Ghizoni MF, Duarte H (2012) Transfer of the distal terminal motor branch of the extensor carpi radialis brevis to the nerve of the flexor pollicis longus: an anatomic study and clinical application in a tetraplegic patient. Neurosurgery 70:1011–1016. https://doi.org/10.1227/neu.0b013e3182367642
41. Zancolli E (1979) Structural and dynamic bases of hand surgery. Lippincott, New York
42. Mangus DJ (1973) Flexor pollicis longus tendon transfer for restoration of opposition of the thumb. Plast Reconstr Surg 52:155–159
43. Bourrel P (1974) Restoration of opposition of the thumb. Apropos of 52 cases. Ann Chir 28:309–317
44. Gupta V, Consul A, Swamy M (2015) Zancolli lasso procedure for correction of paralytic claw hands. J Orthop Surg 23:15–18. https://doi.org/10.1177/230949901502300104