



IFSSH Scientific Committee on Nerve – Spinal Cord Injury

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Update on Hand Surgery in Tetraplegia

ABSTRACT

Patients with cervical spinal cord injury (SCI) suffer from paralysis of all four extremities (tetraplegia). Their foremost goal is to regain autonomy and mobility. Surgical restoration of key functions, such as elbow and wrist extension or hand grip control has tremendous potential to restore critical abilities, e. g. eating, personal care and self-catheterization and productive work in at least 70% of tetraplegic patients. Tendon and nerve transfers, tenodeses and joint stabilizations are time-proven and reliably provide improved arm and hand usability, reduce muscle imbalance and pain in spasticity and prevent joint contractures. Recently, innovative concepts such as single-stage combined procedures have derived from basic scientific research and clinical studies and have been proven to offer considerable advantages over traditional approaches. A combination of seven operations, termed the Alphabet procedure, provides simultaneous active key pinch and global finger grasp, together with passive hand opening and intrinsic function. Immediate activation of transferred muscles is necessary to reduce the risk of adhesions after this extensive surgery, facilitates relearning, and avoids the adverse effects of immobilization on functional recovery. Transfers of redundant fascicles taken from the axillary, musculocutaneous and radial nerve from above the SCI level have been effective and are a promising option to enhance motor outcome and sensory protection after SCI, especially in groups with very limited resources. Further research should be directed at combining traditional algorithms with these new approaches. Improved communication between the medical disciplines caring for these patients, their relatives, and their therapists, should in future help so that more patients can benefit from these advances and could enable many thousands of tetraplegic individuals "to take life into their own hands" and live more independently again.

Key words: Spinal cord injury – tetraplegia – tendon transfer – novel concepts – immediate activation – combined procedure – nerve transfer

PART I: PRINCIPLES

BACKGROUND

Incidence of tetraplegia

The global incidence of spinal cord injury has been estimated between 10 and 80 new cases per million annually. This means that 250-500,000 people worldwide become newly paralyzed every year ¹. The patient population represents mostly young, healthy, and active individuals in their productive years between the 2nd and 4th decade of life. More than 50% of all SCIs occur at the cervical level leading to tetraplegia ². The causes of injury differ between countries but the most common etiologies of traumatic SCI worldwide are motor vehicle accidents, falls, violence and sports and leisure activities. Besides, many SCI occur due to non-traumatic causes, e.g. neoplastic tumors, infection, degenerative or vascular disorders – it can happen to every one of us any day ^{3, 4!}

Tetraplegia hand surgery

Although spinal cord injury remains incurable, surgical rehabilitation of the arm and hand in tetraplegia is a powerful tool to restore upper extremity functions, e.g. the ability to groom, self-feed, self-catheterize, lift objects, write, swim, and drive. Reconstruction of elbow extension improves reaching capabilities and stabilizes the elbow, allowing for further reconstruction of grasping ^{3, 5-8}. Restoration of hand function can eliminate the need for adaptive equipment, allow patients to regain meaningful roles and productive work, markedly improve autonomy and spontaneity and thus enhance self-esteem for persons with tetraplegia ⁹⁻¹¹.

Clinical outcomes

Clinical results have been reported as very positive. In several recent studies, patient perceived outcomes demonstrated major improvement of both satisfaction and performance of preoperatively prioritized daily-activity goals ¹²⁻¹⁵. A meta-analysis of the literature from over 500 cases in 14 studies was recently presented and revealed a mean increase of Medical Research Council score for elbow extension from 0 to 3.3 after reconstruction and a mean postoperative pinch strength of 2 kg, which markedly improved upper extremity usability ¹⁶.

Current utilization

Regrettably, this kind of hand surgery is profoundly underutilized, although outcomes are rated overwhelmingly positive. For example, in the United States with a population of over 100,000 citizens living with tetraplegia, fewer than 400 upper extremity reconstructive procedures are performed per year, indicating that less than 10% of appropriate candidates receive optimal treatment of their upper extremities ¹⁷. The reasons for this underutilization of proven surgical techniques are varied and complex. Many patients are lacking adequate information about the possibility of upper extremity reconstruction ¹⁸.

After patients shift from acute care into long-term non-surgical care, our fractionated health care system is poor at transferring them back into the surgical realm for non-acute conditions. It was suggested that “the biggest barrier to increased use of these procedures is the inadequate referral network between surgeons and physiatrists” ¹⁹.

OBJECTIVE

This paper summarizes the key elements of surgical restoration of arm and hand function in tetraplegia.

1. PATIENT EVALUATION - Anatomy and Clinical Examination

- a. **Muscle Testing:** Surgical planning depends on preoperative sensory and motor evaluation of the upper extremity and includes muscle strength tests according to British Research Council system and International Classification of Surgery of the Hand in Tetraplegia (ICSHT) ²⁰ (Tables 1 and 2). The donor muscle must be healthy and of adequate strength (M4), preferably not injured or re-innervated. With limited available donor muscles, a weaker muscle (M3) may be considered for transfer. Optimally, it should be similar in architecture, synergistic and have an adequate soft tissue bed along the route of transfer ^{21, 22}.

Table 1: Muscle function according to British Research Council system

Muscle Strength Grade	Muscle Function
M0	No active range of motion, no palpable muscle contraction
M1	No active range of motion, palpable muscle contraction only
M2	Reduced active range of motion – not against gravity, no muscle resistance
M3	Full active range of motion, no muscle resistance
M4	Full active range of motion, reduced muscle resistance
M5	Full active range of motion, normal muscle resistance

Table 2: International Classification of Surgery of the Hand in Tetraplegia – with addition of sources for nerve transfers

Group	Spinal Cord Segment	Possible Muscle Transfers	Possible Axon Sources for Nerve Transfers
0	$\geq C5$	No transferable muscle below elbow	Musculocutaneous nerve branches to coracobrachialis and brachialis muscle
1	C5	Brachioradialis (BR)	Axillary nerve branches to deltoid and teres minor muscles
2	C6	+ Extensor carpi radialis longus (ECRL)	Radial nerve branches to supinator muscle
3	C6	+ Extensor carpi radialis brevis (ECRB)	
4	C6	+ Pronator teres (PT)	
5	C7	+ Flexor carpi radialis (FCR)	
6	C7	+ Extensor digitorum	
7	C7	+ Extensor pollicis longus	
8	C8	+ Flexor digitorum	
9		Lacks intrinsics only	
10 (X)		Exceptions	

b. Joint Range of Motion: Passive joint motion, above all in the key joints - shoulder, elbow, wrist, MCP and PIP - is a prerequisite for reconstruction. A tenodesis effect during wrist extension (hand closure) and flexion (hand opening) and joint stability (primarily the thumb CMC joint) is preferable but not required for reconstruction.

c. Sensibility Testing: Sensory examination focus on cutaneous afferents of the hands with a 2-point discrimination, which should be 10 mm or better in the thumb for cutaneous control (Cu). Otherwise ocular control (O) is required ^{10, 20}.

d. Special aspects: Other aspects of neuromuscular examination include identification of brachial plexus lesions and entrapment neuropathies, paralytic spine deformity, thoraco-scapular stability, spasticity, contractures, stiffness and instability of joints ^{23, 24}. Pain and swelling are relative contraindications to surgery and need to be treated before reconstruction.

e. General goals of tetraplegia surgery: To take better advantage of remaining shoulder, arm and hand functions, various philosophies have evolved. Reconstruction of upper limb motor functions in tetraplegia involve multiple surgeries (Tables 3 and 4) but it is always necessary to keep in mind the goals of the

surgeries i.e., to provide the individual with a better ability to perform activities in daily life ^{3, 13, 14}.

2. PLANNING OF RECONSTRUCTION

The main goals of reconstruction are to provide:

1. Elbow extension,
2. Grip function (flexion phase),
3. Opening of the hand (extension phase) and
4. Intrinsic hand function.

The most frequently used procedures to achieve patients' ability goals and algorithm for surgical reconstruction based on International Classification are presented in Tables 3-5.

Prerequisites

In tetraplegia, the following requirements must be met before starting functional operations:

- 1 Neurological functional plateau – no further recovery expected
- 2 Emotional Stability - accepting the consequences of injuries
- 3 No open wounds or pressure sores (decubitus), no infections (e.g. bladder)
- 4 Motivation and ability of the patient to take active part in after-treatment
- 5 Treatment plan based on clinical examination and counseling of the patient
- 6 Available donor muscles (muscle strength grade $\geq M4$)
- 7 Free passive joint mobility ^{3, 8, 10, 25}

Table 3: Summary of possible surgical procedures (excluding nerve transfers) to achieve patients' ability goals

Ability goal	Functional goal	Procedure	Rehabilitation
Stabilizing elbow in space, reaching overhead objects, pushing wheelchair, stabilizing trunk	Elbow extension	Reconstruction of Triceps Function Posterior Deltoid-Triceps Biceps-Triceps	4 weeks cylinder cast with elbow fully extended 4 week orthosis
Use of utensils, hand writing, pushing wheelchair	Grip	Reconstruction of grip Reconstruction of passive key grip BR-ECRB FPL-Radius CMC 1 arthrodesis	4 weeks arm in cast with flexed thumb and wrist 4-10 weeks active exercise
		 Reconstruction of active key grip BR-FPL CMC I arthrodesis Split FPL-EPL tenodesis	4 weeks in orthosis with active key pinch but restriction of wrist extension
Reaching for objects e. g. cup or glass positioning of thumb and fingers for improved grasp control	Opening of the hand	Reconstruction of thumb and finger extensors Passive opening CMC I arthrodesis EPL to extensor retinaculum attachment Active opening PT-EDC and EPL/APL Thumb stabilization ELK procedure, CMC 1 arthrodesis Reconstruction of intrinsics Zancolli-Lasso tenodesis House tenodesis EDM-APB	4 weeks wrist and thumb in cast 4 weeks wrist, fingers and thumb in cast 6 weeks splint for IP / CMC 1 joint with free thumb tip 4 weeks of immobilization in intrinsic plus position Thumb actively exercised 1st postop day

Table 4: Surgery according to International Classification (IC) – excluding nerve transfers

IC group	Recommended surgical procedure
0	<ul style="list-style-type: none"> • Abducted shoulder (anterior deltoid muscle transfer) • Flexion contracture of the elbow (biceps tendon Z-tenotomy) • Supinated but not contracted forearm (Zancolli biceps rerouting - check presence of supinator muscle!) • Fixed supination contracture - osteotomy of radius
1	<ul style="list-style-type: none"> • BR-to-ECRB for active wrist extension • Moberg's key pinch procedure • ELK procedure
2	<ul style="list-style-type: none"> • BR-to-FPL (active key pinch) • CMC 1 fusion • ELK procedure • EPL tenodesis to dorsal forearm fascia
3	<ul style="list-style-type: none"> • BR-to-FPL • ECRL-to-FDP 2-4 • ELK procedure • House intrinsic procedure • CMC 1 fusion • EPL-tenodesis
4	<ul style="list-style-type: none"> • BR-to-FPL • ECRL-to-FDP 2-4 • ELK procedure • House intrinsic procedure • CMC 1 fusion • EPL-tenodesis
5	<ul style="list-style-type: none"> • BR-to-FPL • ECRL-to-FDP 2-4 • ELK procedure • House intrinsic procedure • CMC 1 fusion • EPL-tenodesis
6	<ul style="list-style-type: none"> • BR-to-FPL • ECRL-to-FDP 2-4 • ELK procedure • House intrinsic procedure • EDM-to-APB transfer • EDC-to-EPL
7	<ul style="list-style-type: none"> • BR-to-FPL • ECRL-to-FDP II-IV • ELK procedure (if required) • House intrinsic procedure • EDM-to-APB or EIP-to-APB
8	<ul style="list-style-type: none"> • BR-to-FPL • ECRB activated ADPB • Opponens plasty (EIP, EDM, FCU) • Active Zancolli lasso procedure (ECU) • House intrinsic procedure
9	<ul style="list-style-type: none"> • House intrinsic procedure
10	<ul style="list-style-type: none"> • Pathological postures (MP joints fixed in hyperextension, lack of any functioning intrinsic muscles, wrist fixed either in flexion or extension etc.) • Release of contracted muscles, joint capsules, tendon lengthenings

Table 5: Surgical management of spasticity in the tetraplegic upper extremity

Spasticity	Affected muscles	Surgical procedure	Function
Forearm	Pronator teres	Release	Supination possible
Wrist	FCR, FCU	Tendon lengthening	Wrist extension possible
Thumb	FPL, AdP	Tendon lengthening	Thumb extension and opening of 1st web space possible
Fingers	FDS / FDP	Tendon lengthening	Hand opening
Fingers	Interossei	Release	Reduction of intrinsic tightness, better grip

Time management

The above-mentioned conditions are usually achieved only after completing the first rehabilitation, yet a strict time rule (e.g. no operations before one year since injury) is not appropriate. Some patients achieve a stable neurological level after 3-6 months, especially in cases of complete tetraplegia. Early hand rehabilitation has many advantages, such as faster reintegration. Often, however, financial, family or work-related problems must be solved first. In incomplete tetraplegia, functional recovery may occur even long time after the injury (about two years). On the other hand, a reconstruction using tendon transfers may remain meaningful even decades after the spinal cord injury. Predictability is reduced in incomplete SCI with asymmetry and spasticity, so that a treatment plan should be developed only after nerve regeneration is complete and spasticity is under control ²⁶.

Nerve transfers require a different perspective. Paralyzed muscles in SCI can be categorized into 1. functional muscles innervated by the supraspinal segment and still under voluntary control, 2. muscles innervated by neurons at the lesion level with damaged anterior horn cells resulting in a lower motor neuron denervation 3. muscles innervated by infraspinous segment which are paralyzed. Preservation of the anterior horn cells results in an upper motor neuron paralysis of these muscles. The nerves to the first group of muscles represent potential donor nerves, the nerves to the latter two groups are potential recipients for nerve transfer surgery. Early surgery (optimally within a year) is critical regarding the denervated muscle group as neuromuscular end plate degeneration will make the muscle refractory to eventual reanimation. If a muscle is paralysed by an upper motoneuron lesion, neuromuscular degeneration will likely be slowed and this may extend the time limit for successful reanimation with nerve transfers ^{27, 28}.

PART II: OPERATIVE TECHNIQUES

1. Reconstruction of Elbow Extension

Elbow extension is critical for overhead activities, weight shifting and transfers, greatly improves wheelchair propulsion and increases the workspace of the hand in space by 800%. Elbow reconstruction should precede grip reconstruction because

- Use of a hand that cannot reach out is very limited.
- Elbow extension helps to stabilize the patient's trunk in the wheel chair
- Stability itself is a factor for more controlled use of the hand
- Function of distal tendon transfers are improved, e.g. brachioradialis muscle function (as a donor) requires a counteracting and stabilizing action from its antagonist i.e. elbow extension.

Two surgical options are advocated to restore active elbow extension

a. Muscle transfer by

- Posterior deltoid-to-triceps transfer^{9, 29-31} or
- Biceps-to-triceps transfer³²

Posterior deltoid-to-triceps transfer reliably restores lost elbow extension in patients with C5/6 tetraplegia. Patient candidates for biceps-to-triceps transfer usually demonstrate intact and functional brachialis and supinator muscles, biceps spasticity and an elbow flexion contracture exceeding approximately 20°. Both techniques are time-proven and provide the tetraplegic with improved arm control for many daily activities³¹⁻³² (Fig. 1).



Figure 1: C5-C6 tetraplegic patient demonstrates her elbow extension after bilateral posterior deltoid to triceps reconstructions.

b. Nerve transfer using axons from the axillary nerve

Alternatively, triceps reanimation is possible by nerve transfer. Possible donors are nerve branches of the posterior portion of the axillary nerve (to posterior portion of deltoid or teres minor muscle) or the brachialis branch of the musculocutaneous nerve³³⁻³⁵.

2. Reconstruction of Forearm Pronation

A supination contracture can be defined as an inability to stabilize the hand in pronation due to an imbalance between the functional supinator muscles, mainly the biceps brachii and supinator, and the hypotonic or paralyzed pronators. Initially a supination contracture can be reduced with abduction and internal rotation of the shoulder, but over time it becomes permanent as the biceps brachii and the interosseous membrane contract. Apart from looking ‘odd’, a supination contracture seriously impairs hand function, which albeit rudimentary, is very important to the tetraplegic patient. A supination deformity increases the risk of developing a gravity-induced extension contracture of the wrist. Correction of the supination deformity enhances the usefulness of any remaining functional muscles by enabling key-pinch. It is generally agreed that functional surgery should aim to restore the pronated position of the forearm and surgical options include:³⁶

- a. **Distal Transposition of Biceps Tendon (rerouting)**, if necessary with interosseous membrane release .
- b. **Dorsal Transposition of the Brachioradialis** during BR-to-FPL transfer to achieve simultaneous thumb flexion and forearm pronation^{37, 38}.
- c. **Derotation Osteotomy of the Radius**³⁶.

3. Reconstruction of Wrist Extension

a. Tendon Transfer (BR-to-ECRB):

Reconstruction of active wrist extension is of utmost importance due to the wrist-related tenodesis effect. If wrist extension is absent (IC groups 0 and 1), the brachioradialis (only IC group 1) can be transferred for wrist extension to the ECRB to obtain a wrist extension without radial deviation, and stable wrist-extension-driven key pinch can be provided by FPL tenodesis to the radius (Moberg procedure) (Fig. 2)^{39, 40}.



Figure 2: C6 tetraplegic patient holding knife 4 weeks post grip reconstruction by transferring the BR to the ECRB and FPL tenodesis to the radius (Moberg procedure)

- b. **Nerve transposition from above the elbow:** Active wrist motion enabling a tenodesis grip is a key function in high level tetraplegia. However, antigravity wrist extension is absent in C5 tetraplegia and this renders inability to perform even the simplest activity of grip, sensory functions and human contact. The basic passive key pinch cannot be restored by traditional transfers in patients with no available donor muscles below the level of elbow. A tenodesis grip can be restored by the transfer of the brachialis motor nerve to the ECRL motor nerve, combined with tenodesis of the FPL to the radius⁴¹. This group forms a relatively large proportion of the overall tetraplegia population. In larger series, IC groups 0 and 1 are relatively frequent and correspond to 28% of 222 patients from our center⁴².

4. Positioning and stabilization of the thumb

Flexion of more than 60° in the interphalangeal (IP) joint significantly disturbs thumb function in patients who have preserved or reconstructed extrinsic flexor function (by flexor pollicis longus muscle), but have paralysis of antagonistic intrinsic or extrinsic thumb muscles due to peripheral nerve lesions, spinal cord injury or neuromuscular diseases.

The preferred operation is currently the EPL knot (ELK) procedure⁴³ which is a duplication of the EPL tendon at the level of the IP joint to prevent hyperflexion. A V-shaped incision is made over the extensor hood, the EPL tendon is elevated with a hook and a loop is formed and anchored with two sutures at its basis. The loop is then folded proximally on the EPL tendon and fixed with sutures along its three sides while IP joint is extended.

5. Reconstruction of Grip Function

Tetraplegic patients usually have a spontaneous weak pinch between the thumb and index finger, depending on the presence of a wrist extension – tenodesis grip. To produce a useful grip, preoperative planning must be based on the patient's goals and wishes and thorough testing of muscle function, sensibility and spasticity of the hand. In IC group 2 patients, active extension of the wrist depends only on the ECRL muscle, therefore this muscle must not be used for a transfer in this group of patients. In IC groups 3 and higher, where active extension is provided by both the ECRL and ECRB, the ECRL can be used for active transfers^{3, 42}.

- a. **Reconstruction of Key Pinch** - Lateral pinch, termed key grip, is based upon the fact that hand opens by passive or active wrist flexion and closes by wrist extension, whereby the thumb pulp ideally should meet the radial side of the middle phalanx of index finger. Prerequisites for passive key grip are wrist extension, minimum strength grade 3, forearm pronation and an acceptable relationship between thumb and index/long finger. Stabilizing procedures are the ELK distal thumb tenodesis and CMC I arthrodesis. Active key pinch is preferably achieved by a BR-FPL tendon transfer⁴⁴.
- b. **Reconstruction of Power Grip - ECRL-to-FDP tendon transfer** - Active whole hand closure is powered by an ECRL tendon transfer to the deep finger flexors of index, middle and ring fingers, excluding the little finger to prevent hyperflexion (Fig. 3)⁴⁴.



Figure 3: Intraoperative view of ECRL-to-FDP tendon transfer for restoration of finger flexion.

- c. **Nerve transfer to Restore Interosseous Anterior Nerve Function** - Transferring the brachialis motor branch of the musculocutaneous branch to the anterior interosseous branch of the median nerve can be used to reanimate finger and thumb flexion^{45, 46}.

6. Reconstruction of Intrinsics

The purpose of interossei/lumbrical reconstruction is to obtain MCP joint flexion and PIP and DIP joint extension. Key pinch can be achieved by positioning the index finger so that it is sufficiently flexed to meet the thumb and is also supported by digits 3-5. Secondly, extension of the PIP joints is essential for grasp and release and provides a more normal opening of the hand than reconstruction of EDC function which gives an intrinsic minus manner of opening. The House procedure has proven superior to the formerly used Zancolli lasso plasty in our experimental and clinical experience ^{47, 48}.

a. Passive Interossei Function of the Fingers using Passive Tenodesis by Tendon Grafts in the Lumbrical Canals – House procedure ⁴⁹.

b. Reconstruction of Active Interossei Function by Tendon Transfer, e.g. FDS 4 with 4 Tendon Slips in the Lumbrical Canal – Brand Procedure

Active intrinsic hand function may be reconstructed by using a motor muscle with 4 tendon slips inserted into the lumbrical canals as developed by Brand, primarily for leprosy patients with combined median and ulnar nerve palsy.

c. Restoration of Palmar Abduction of the Thumb

Thumb palmar abduction can be restored by transferring extensor digiti minimi (EDM) to the insertion of abductor pollicis brevis (APB). Notably, for this reconstruction M3 power of the EDM is usually sufficient to increase first web space opening and to position the thumb optimally alongside the index finger ⁵⁰.

7. Reconstruction of Hand Opening (Extensor Phase)

Reconstruction of hand opening is necessary to facilitate the ability of the fingers to surround an object in order to grasp (Table 3). Many of the tetraplegic patients do not have this ability due to the “tenodesis grip” which occurs with wrist extension and is due to adhesions of the finger flexors and insufficient extension of the fingers even with good passive wrist flexion. Improvement of the opening of the hand is particularly necessary in patients with finger flexor spasticity where gravity or remaining finger extension strength cannot overpower the finger flexion spasticity ⁵¹.

a. Passive Opening of the 1st Commissure by EPL tenodesis to extensor retinaculum or forearm fascia (powered by active or passive wrist flexion).

b. Active Opening by Tendon Transfer by transferring PT to EPL, APL and EDC

c. Nerve Transfer of the Supinator Motor Branches (C6) to the Posterior Interosseous Nerve (C7-8) – Bertelli S-PIN Procedure - Bertelli described the possibility of using the fact that supinator is always C6-innervated and is redundant when biceps is intact, while the fibers of the posterior interosseous nerve roots are

C7-8-innervated. By transferring the expendable supinator motor branches to the posterior interosseous nerve, finger and thumb extension as well as ECU function can reinnervated^{34, 52}.

8. Alignment of wrist position by ECU tenodesis

Often there is a radial deviation of the wrist due to the limited active flexion and extension and lack of ulnar deviators, especially in groups 0 and 1, in which only the ECRL is strongly present. By suturing of a tendon loop onto the ECU tendon itself, the gripping force, in comparison with an unbalanced hand with the same motion, doubles. Because of ergonomic hand function, the shoulder does not externally rotate when the wrist is radially deviated. This can reduce the shoulder pain that occurs often in quadriplegics⁵³.

9. Additional Procedures to Reduce Spasticity

A common observation over the past years is the increasing number of incomplete tetraplegics. These patients present a somewhat new configuration and a more complex functional loss than that of those patients with complete tetraplegia, and often demonstrate various degrees of spasticity and muscle-joint deformities⁵¹. Muscle stiffness, imbalance and deformity can frequently be corrected by muscle release and/or tendon lengthening procedures (Table 5)^{51, 54}.

Mild deformities in the hand primarily affect the PIP and DIP joints while the MCP joints are usually spared. Severe deformities may affect all finger joints. Certain surgical techniques have proven successful in treating spasticity:

- a. Littler Release** - In many cases a partial resection of the oblique part of the extensor aponeurosis is enough. The insertion of the interossei on the proximal phalanx remains. The operation time is short and this produces an immediate result⁵⁵.
- b. Tendon Lengthening of the Extrinsic Finger Flexors (FDS/FDP)** - Tenotomies of the flexors are performed about 5 cm proximal to the carpal canal using a step-cut incision of 6-8 cm in length. This allows a parallel sliding of both tendon stumps and subsequent prolongation of 2-3 cm⁵¹.
- c. Additional Procedures** - In some cases other procedures may be required, such as releases of muscle insertions, e.g. the adductor pollicis or pronator teres or a tenomyotomy of the wrist flexors.

INNOVATIVE CONCEPTS

1. Combined Procedures - Active Flexor and Passive Extensor Phase with Intrinsic Reconstruction⁵⁶

Traditionally, operations for flexors and extensors were separated, yet we have successfully combined procedures for active key pinch and finger flexion together with passive opening of the hand as a one-stage operation. This reconstruction includes 7 individual operations performed in the following order: 1) Split FPL-EPL distal thumb tenodesis, 2) Reconstruction of passive interosseous function, 3) thumb CMCJ arthrodesis 4) BR-FPL tendon transfer, 5) ECRL-FDP tendon transfer, 6) EPL tenodesis, 7) ECU tenodesis. This reconstruction is termed the Alphabet or ABCDEFG procedure, abbreviation for Advanced Balanced Combined Digital Extensor Flexor Grip reconstruction (Table 6).

Table 6: Advanced Balancing Combined Digital Extension Flexion Grip (ABCDEFG) Reconstruction

Order	Procedure	Type	Motor	Function	Effect
1	ELK procedure	Tenodesis	Active ¹	Stabilize IP joint	Prevent hyperflexion of IP joint, Increase contact surface to index
2	Free tendon transplant (FDS4, PL, Plantaris) → extensor hood digits 2-3 and 4-5	Tenodesis	Passive ²	Interossei ³	Opening hand
3	CMC 1 joint stabilisation	Arthrodesis	N/A	Fusion of base of the thumb and correct deformity	Secure thumb's approach against index during key pinch
4	BR-to-FPL	Tendon Transfer	Active	Thumb flexion	Key pinch
5	ECRL-to-FDP 2-4	Tendon Transfer	Active	Finger flexion	Power grasp
6	EPL-to-dorsal forearm fascia	Tenodesis	Passive ²	Extend thumb	Opening hand
7	ECU-to-ulnar head	Tenodesis	Passive	Prevent radial deviation of wrist	Balance hand position at all types of grips

¹ powered by BR-to-FPL, ² powered by wrist flexion, ³ MCP joint flexion, PIP / DIP joint extension

To reduce the risk of adhesions after this extensive surgery and to facilitate relearning, the activation of transferred muscles with new functions requires early active postoperative training. One-stage reconstruction can reliably provide grip, grasp and release function in

persons with C6 tetraplegia (Fig. 4). Patient compliance and satisfaction is high. Overall, this simultaneous reconstruction saves time, limits the need for immobilisation and the effort of patient and caregivers are less compared to the standard 2-stage reconstructions. The incidence of complications is comparable with other published treatment methods ⁵⁷.



Figure 4: Patient with C6 tetraplegia shows hand-writing technique before (left) and 4 weeks after (right) one-stage complete grip reconstruction (Alphabet procedure ^{56,57}).

2. Immediate Activation of Transferred Tendons

The most remarkable and effective strategy of improving function has been the consistent and immediate activation of transferred muscles after surgery. Early active training of new motors not only prevents the formation of adhesions but facilitates the voluntary recruitment of motors powering new functions, before swelling and immobilization-induced stiffness restrain muscle contractions. Additionally, the patient will experience an early, spectacular and inspiring effect of the reconstruction, which will help motivate training during the demanding and sometimes painful initial postoperative period ⁵⁸. Early activation of the transferred muscles requires reliable tendon-to-tendon attachments. We have accumulated experience of hundreds of side-to-side attachments using running sutures back and forth along both sides and with a minimum of 5 cm overlap (Fig. 5) ⁵⁹.



Figure 5: BR-to-FPL tendon attachment site using double-sided running sutures back and forth with 5 cm overlap.

This technique has proven extremely safe for allowing early active training, even in cases of donor and recipient tendon mismatch, and is now standard in our unit ^{3, 60}. Tendon force measurements have confirmed the assertion that the elbow joint need not be immobilized when the BR is used as a donor muscle in tendon transfer to the FPL, as the maximum passive tendon tension was only about 20 N in our cadaveric model and the failure strength of this specific repair was over 200 N ⁵⁹. We suggest that it is possible to perform multiple tendon transfers in a single stage, avoiding the adverse effect of immobilisation. Briefly, the day after surgery a removable splint replaces the cast and intermittent exercises commence. Training emphasizes the activation of donor muscles with slight external resistance.

3. Nerve transfers

Additional reconstructive options could be achieved by nerve transfers, i.e. extra-anatomical short-circuit between expendable donor nerve fascicles from above the level of the spinal cord injury and the motor branch of a paralyzed muscle below it. Nerve transfers have been established in recent years, especially in brachial plexus lesions, but are rarely applied in tetraplegia⁶¹⁻⁶³. Ideally, the coaptation of an expendable pure motor axon donor with the recipient branch should be over the shortest possible distance⁴¹. Theoretically, suitable donor nerves include:

- Axillary nerve (C5/6) branches to the posterior deltoid and teres minor to restore elbow extension^{34, 52}
- Radial nerve branches to the supinator (C6) or ECRB (C7)^{46, 47} for thumb or finger extension
- Musculocutaneous nerve branches to coracobrachialis or brachialis muscles for elbow extension, wrist extension or finger and thumb flexion^{41, 45, 46, 60}
- Superficial radial nerve (C6) or lateral antebrachii cutaneous nerve (C5/6) for sensory restoration of the median nerve (1st web space) in patients categorized as 0 (ocular control)⁶³

Theoretically, nerve transfers in SCI may even be more effective compared to peripheral nerve injury because recipient muscles with intact lower motor neurons preserve reflex arcs. They should not become refractory to reinnervation / external stimulation after 18-24 months as occurs after peripheral palsy. Axon transfer from the intact donor nerve may allow highly selective neurotization by intraoperative fascicle stimulation of the intact recipient nerve, minimizing the distance between donor and recipient and, therefore, regeneration time. Furthermore, natural biomechanics, the force and excursion of the original muscle are preserved, and scar-induced motion restrictions are prevented without the need for extended immobilization – a primary factor why appropriate candidates refuse muscle transfers. Axon transfers may provide options for patients not amenable to conventional tendon transfers, including IC group 0^{3, 41, 45, 46}.

Combining tendon transfers and nerve transfers

Further research should be directed at combining traditional algorithms with these new approaches, such as in the case reported by Bertelli and Ghizoni⁶⁴, restoring elbow extension, finger extension (MCP joint), thumb extension and pinch, is a fine example of the potential restoration of upper limb function that can be achieved by combining tendon and nerve transfers in one surgery. Both techniques, muscle and nerve transfer, need to be carefully considered and individualised according to their advantages⁶⁵. For example, the Bertelli S-PIN procedure (supinator to posterior interosseous nerve transfer) may achieve better hand opening compared to pronator to EDC tendon transfer. This nerve transfer reanimates not only the finger extensors, as does the tendon transfer, but also allows independent thumb extension and abduction and first web opening by reinnervating the APL, and wrist centralization by also reinnervating the ECU muscle. On the other hand, the classical BR-to-FPL tendon transfer almost immediately provides strong pinch, which may exceed the power achieved by a nerve transfer to restore anterior interosseous nerve function after a lengthy regeneration period.

TEAM APPROACH

Tendon transfer procedures are optimally undertaken with a team approach, using the assistance of an occupational and a hand physiotherapist as well as a surgical nurse. The essential hand therapist performs the “other half” of the surgical procedure, rehabilitation and retraining of the transferred tendons. The hand therapist promotes functional restoration, assists with edema control, contracture prevention, and muscle activation and strengthening. Many patients who undergo tendon transfer procedures have sustained devastating, life-changing injuries and they should be considered full members of the rehabilitation team. Their input is required in the preoperative planning so the patient understands operative options and alternatives, and appreciates the commitment required for successful rehabilitation ³.

CONCLUSION

Every person who sustains a cervical spinal cord injury with tetraplegia should be examined, assessed and informed concerning the options of possible reconstruction of motor function of the hands and arms. It is of course a long way before this ambitious goal can be achieved but the resolution put forward by the leading experts in this field certainly stresses the necessity of increasing the awareness and improving the infra-structure to meet patients’ demands of informed discussions of options for improvement of hand function. Many patients are now better informed about the benefits of surgery probably because of easy access to comprehensive web pages on the Internet, a trend that will likely increase the demands for more surgical reconstructions in the future. The overall goal of treatment is to improve motor functions in order to achieve a higher degree of independence for the individual with tetraplegia. Individuals with stable non-traumatic SCI, though differing from traumatic SCI regarding demography and injury patterns, can benefit similarly from surgical rehabilitation of their upper extremities.

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ABBREVIATIONS

APB	Abductor Pollicis Brevis
APL	Abductor Pollicis Longus
BR	Brachioradialis
CMC	Carpo-Metacarpal
DIP	Distal Inter-Phalangeal
ECU	Extensor Carpi Ulnaris
EDC	Extensor Digitorum Communis
EDM	Extensor Digiti Minimi
ECRB	Extensor Carpi Radialis Brevis
ECRL	Extensor Carpi Radialis Longus
EPL	Extensor Pollicis Longus
FDP	Flexor Digitorum Profundus
FDS	Flexor Digitorum Superficialis
FPL	Flexor Pollicis Longus
MCP	Meta-Carpo-Phalangeal
PIP	Proximal Inter-Phalangeal
PNI	Peripheral Nerve Injury
PT	Pronator Teres
SCI	Spinal Cord Injury