Hand Surgery and Rehabilitation 39 (2020) 474–486

Available online at
ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com

History of hand surgery

40 years of experience in functional surgery of the tetraplegic upper limb

40 ans de chirurgie fonctionnelle du membre supérieur du tétraplégique

Y. Allieu

Institut Montpelliérain de la Main et du Membre Supérieur (IMM), Polyclinique Saint Roch, 560, rue du Colonel Pavelet, 34070 Montpellier, France

ARTICLE INFO

Article history:
Received 8 April 2020
Received in revised form 28 May 2020
Accepted 28 May 2020
Available online 8 August 2020

Keywords:
Tetraplegia
Spinal cord injury
Cervical spine fracture
Upper extremity paralysis
Grip reconstruction
Spasticity

ABSTRACT

The author relates his 40 years of experience in the field of functional surgery of the tetraplegic upper limb (FSTUL). After having introduced and developed this specialty in France, he disseminated it to various countries where he saw a large number of patients and acquired extensive experience. He presents his personal progression and discusses the recent therapies in this field. FSTUL is a personalize surgery, with each case being unique. It must, first and foremost, take into consideration the real wishes of a motivated and well-informed patient and consider the type of spinal cord injury (not only the upper level of the lesional segment but also the extent of the sub-lesional segment). The surgical indication and rehabilitation are very important factors in the outcome. The main goal of FSTUL is rapid social reintegration of the patient; in some cases, this could involve fewer surgical procedures and shorter stays in rehabilitation centers. FSTUL is in constant evolution and can be improved; it is a useful but not well-known surgery.

Mots-clés:
Tétraplégie
Traumatisme médullaire
Fracture du rachis cervical
Paralysie du membre supérieur
Construction d'une préhension
Spasticité

RÉSUMÉ

L'auteur relate ses activités durant 40 ans concernant la chirurgie fonctionnelle du membre supérieur du tétraplégique (CFMST). Après avoir introduit et développé cette spécialité en France, il en a fait de même dans d'autres pays, lui permettant de voir de nombreux malades et d'acquérir ainsi une importante expérience. Il expose son évolution personnelle et discute des nouveautés apparues en ce domaine. La CFMST est une chirurgie personnalisée adaptée à chaque cas. Elle doit tenir compte: 1) Avant tout des désirs réalistes d'un patient motivé et informé. 2) Du type de la lésion médullaire (non seulement de son niveau supérieur, mais aussi de l'étendue des segments lésionnel et sous-lésionnel). 3) L'indication opératoire et la réhabilitation sont de première importance. Le but de la CFMST est une rapide réinsertion socioprofessionnelle nécessitant, si possible, la réduction du nombre des temps opératoires et la durée des séjours en rééducation. La CFMST est en constante évolution et peut être améliorée mais est actuellement une chirurgie très utile et insuffisamment connue.

1. Introduction

I want to share my 40-year career in functional surgery of the tetraplegic upper limb (FSTUL). Following the experience that I acquired over the years, I will discuss this surgery as I have taught it and developed it in France and abroad.

I met Eric Möberg in 1980 when I was Professor of orthopedic surgery. I became interested in FSTUL and developed this discipline, which I introduced in France [1]. This has remained, to this day, one of my main interests in surgery of the hand and upper limb [2–4]. Eric Möberg was and will always be, my mentor [5–8].

In 1983, under the initiative of neurosurgeon Professor C. Gros, I cofounded the Propara Center in Montpellier, France. This center was the first of its kind in the world to specialize in the

E-mail address: yves.allieu@wanadoo.fr

https://doi.org/10.1016/j.hansur.2020.05.012
2468-1229/

management (rehabilitation, but also surgery and research) of spinal cord injuries. Our pioneering institute attracted many overseas visitors, including the most prominent international specialists in the field of tetraplegia. The same year, in 1983, I organized a post-conference meeting at Propara following the 2nd Spinal Cord Meeting in Giens on the behest of E. Möberg. During this meeting, a small but passionate group of international specialists in this new and upcoming field, established the International Classification (IC) to harmonize their ideas [9]. The discussions among specialists in Giens and then at Propara were very fruitful.

In 1988, I had a serious accident and my career was interrupted for 3 long years. Three years after the accident, I returned in 1991 to my previous position at the Montpellier University Hospital and the Faculty of Medicine, but was forced to reduce my surgical activities, which gave me more time to travel and develop FSTUL.

In 1992, one year after resuming my activities, I organized an international meeting in Montpellier on FSTUL and Tetraplegia and Sport with J. House and E. Möberg. During the rest of my career, apart from my activities at Propara [10], I developed FSTUL and regularly trained surgeons in France and overseas: Strasbourg (from 1993 to this day), Giens (from 1998 to this day), Martinique (1994 to 2002), La Réunion Island (2001 to 2005), Italy (1994 to 2000) and Germany (2002 to 2007). I acquired extensive experience thanks to my travels, with each case being unique, thus following in Eric Möberg's footsteps.

After retiring at the age of 65 as Head of the Upper Limb Orthopedic Surgery Department at the University Hospital in Montpellier, I founded the private IMM Institute (Hand and Upper Limb Institute of Montpellier) with former collaborators, where I am the scientific director and consulting surgeon to this day. I continue sharing my experience in tetraplegic surgery in Strasbourg, Giens and in Las Palmas (Spain).

FSTUL is not only a reconstructive procedure but also a surgical rehabilitation procedure. One must forget the classical concepts of surgical reconstruction and focus on the patient's personal desires to lead a better life despite its myriad of problems. Surgical rehabilitation of the tetraplegic patient is always a challenge, because each one is unique, with his or her own remaining physical abilities, wishes, and expectations. Thus, establishing surgical indications based solely on the level of the spinal cord injury and the possibilities of the remaining transferable muscles is a course of action that indicates only *what can be done, not what should be done*. The surgeon must consider the individual patient's requirements. This type of surgery can be practiced only with a team of physical and occupational therapists at highly specialized centers. The precise indications are difficult to establish, when based only on limited experience. Despite the large number of cases that I have seen in my 40 years of experience in France and abroad, I am still always surprised when I see a new case that is totally different from the others. When dealing with FSTUL one must answer three main questions: ***When? Who?* and *What?***

2. When?

2.1. As early as possible

We have learned from our experience that operating on the patient before he or she adapts to the injury is essential. If a tetraplegic patient is treated too late, the surgery will still provide him or her with new functional possibilities, but the patient will not be able to benefit from them because new adjustments must be made. There would be academic results, of course, but they may not be of any practical use to the patient. *He (she) could use these possibilities but will he (she) really do it?* Tetraplegia that has existed several years is more often a contraindication to surgery; however, even in these cases, there is no general rule against surgery, as long as the patient yearns for a specific functional improvement.

2.2. When it becomes feasible

Generally, FSTUL should be considered only 12 to 18 months after the injury. We believe, as do others, that this wait can be shortened to around 6 months. The surgery must be performed as early as possible but should be considered only when the tetraplegia has stabilized (i.e., only after motor improvement has ceased). Important and uncontrolled spasticity, pain, and neurovegetative complications should be treated first, and pressure sores and problems with urinating and defecating should be remedied as well. The patient must be able to sit in a wheelchair so that he or she can move the upper limbs against gravity. We insist on the fact that joints condition must be treated from day one. This should be considered as an emergency in the centers that receive tetraplegic patients. If this is not the case, preoperative rehabilitation will be needed for a poor condition with secondary stiffness:

- Passive flexion of the metacarpophalangeal (MCP) joints must be an average of 30 degrees. MCP hyperflexion secondary to flexor hypertonia must be corrected.
- Hyperflexion of the proximal interphalangeal (PIP) joints must be avoided or treated early. Prolonged hyperflexion results in weakening of the central band of the extensors at the dorsum of the PIP.
- The thumb and index must be well-positioned in the pinch grip position.
- Stiffness of the wrist in flexion must be overcome to allow thumb and finger opening via passive wrist flexion due to gravity.
- Passive elbow extension must be complete to allow elbow locking in extension.
- Supination contracture must be prevented through rehabilitation from the first day of tetraplegia. This posture is severely debilitating. Supination contracture results in a fall of the wrist and secondarily stiffness of the wrist in extension preventing spontaneous pinch grip [11].

3. Who?

3.1. A good candidate – motivated, well-informed patient with precise and realistic needs

Individual factors such as age, profession, hobbies, education, family support, and social background must be considered. Most of the unsatisfactory outcomes of FSTUL are the result of incorrect patient selection. The surgeon must establish a contract with the patient, who must commit to it fully. Videotapes showing the pre- and postoperative condition of patients who have undergone the same surgery can help new patients understand the possibilities being offered. In a specialized center, the patient is in contact with others in similar situations who may have already undergone surgery, thus demonstrating the surgical possibilities. The roles of physical therapists and medical teams but also paramedical teams composed of nurses and medical assistants who have close contact with the patient are of prime importance.

3.2. Types of spinal cord injuries

The spinal cord lesion is not clear-cut. The lesions are frequently asymmetrical. Moreover there may be unusual patterns of certain motor and sensory functions being spared.

3.2.1. Two spinal cord segments

We can differentiate two spinal cord segments in the tetraplegic cervical spine [12]:

- A lesional segment (LS), in which the lower motor neurons (LMN) are damaged with denervation and atrophy of corresponding muscles like in peripheral palsy. The upper limit of the LS determines the tetraplegia level.
- A sublesional segment (SLS), in which the LMN are intact with medullary reflexes like in central palsy, with muscular tone and no atrophy. The SLS is spared and, although it no longer responds to the central command, it still has independent activity leading to some muscle tone and different degrees of spasticity. In tetraplegia, both central and peripheral palsies can occur.

There are two types of paralyzed muscles: those with LMN damage and those without. Clinical and paraclinical studies of muscles allow us to differentiate between these two medullary segments. These two segments can be seen on MRI of the spine (Fig. 1).

3.2.2. The International Classification of Giens

The IC for each upper limb, established in Giens in 1984, is based on the number of transferable healthy muscles above the LS present in the forearm graded ≥M4 according to the Medical Research Council (MRC) and discriminative sensibility in the thumb-index pinch with a two-point discrimination of 10 mm for cutaneous control (graded as Cu), otherwise the control is only ocular (graded as O) (Table 1). The IC defines the upper level of the LS and classifies 11 groups from G0 to G10:

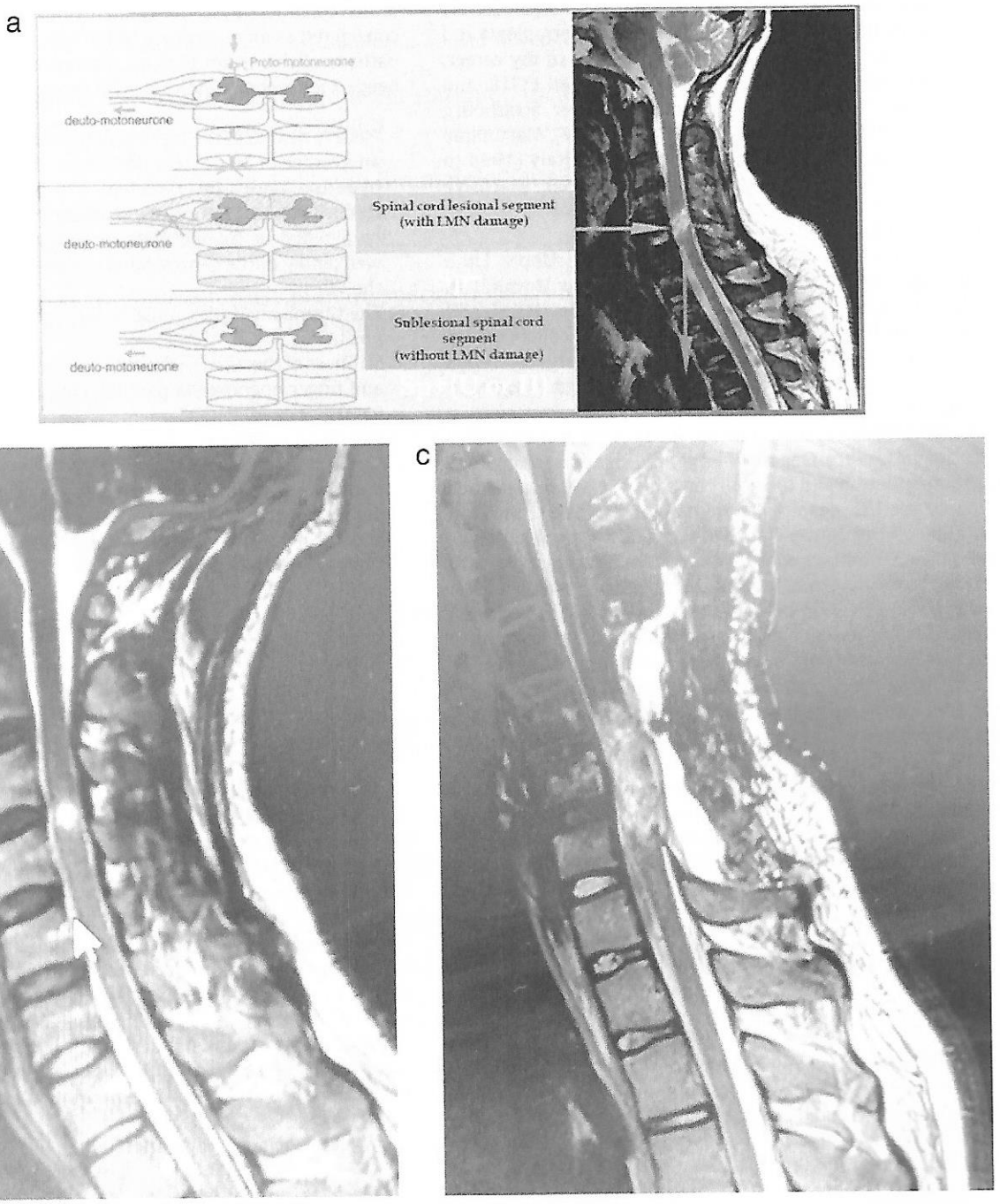


Fig. 1. The two tetraplegia spinal cord segments. The lesional segment (LS) and the sub-lesional segment (SLS) (A). MRI: Short lesional segment and extended sub-lesional segment (B). MRI: Spinal cord injury that extends lengthwise (C). *LMN*: lower motor neurons.

Table 1
International Giens classification (IC) [9].

Sensibility:	Group O or O Cu
Group 0:	No muscle below elbow suitable for transfer
Group 1:	BR > 4
Group 2:	+ECRL > 4
Group 3:	+ECRB > 4
Group 4:	+PT > 4
Group 5:	+FCR > 4
Group 6:	+Finger extensors > 4
Group 7:	+Thumb extensor > 4
Group 8:	+Partial digital flexors > 4
Group 9:	Lacks only intrinsics
Group 10:	Exceptions

BR: brachioradialis; *ECRL*: extensor carpi radialis longus; *ECRB*: extensor carpi radialis brevis; *PT*: pronator teres; *FCR*: flexor carpi radialis.

- In Group IC.G0, there are no muscles below the elbow graded ≥4 and no possibility of functional surgery of the hand using muscle transfer. The only solution would be functional neurostimulation of the SLS if stimulable [13,14]. Because this technique is so demanding, we could not use in the various European and overseas centers where we worked because it can only be used in highly specialized centers, since as those in the United States. In this group, surgery is sometimes necessary to correct incorrect postures (wrist hyperflexion, elbow hyperflexion, forearm supination contracture), but this is a corrective surgery and not a functional surgery.
- In Group IC.G10, there are cases that cannot be classified. I have noticed over the years that these are more and more frequent, due to premature surgery on fractures of the cervical spine.

3.2.3. Personal modifications of the IC

We have slightly modified and added to the IC [15] to differentiate between three main groups of tetraplegic patients for FSTUL. We must emphasize this classification is only schematic and didactic, serving solely as a guide for surgery, since every case is unique. We recognize three types of tetraplegia: high, mid, and low-level (Table 2).

- High-level tetraplegia (IC.G1-IC.G2) is characterized by only one transferable muscle: the brachioradialis (BR). The triceps brachii (TR) is paralyzed on both sides (TR−).
- In IC.G1, only the BR is present and available for transfer. There is no wrist extension.
- In IC.G2, the extensor carpi radialis longus (ECRL) is present along with the BR. Since it extends the wrist, it must not be transferred. Active wrist extension is very important for the tetraplegic patient. There are two types of tetraplegic patients, those who have active wrist extension and those who do not. There is an important functional difference between these two types, since those with active wrist extension can have a spontaneous key pinch grip.
- Mid-level tetraplegia (IC.G3-IC.G4-IC.G5) defined by strong wrist extension due to the extensor carpi radialis longus and brevis (ECRL and ECRB). In mid-level tetraplegia, the TR may (TR−) or may not (TR+) be paralyzed on both sides or only on one side.
- In IC.G3, the ECRB is present and strong wrist extension is due to the two extensor carpi radialis (ECR) muscles.
- In IC.G4, the pronator teres (PT) is present as well as the BR and the two ECR muscles.
- In IC.G5, the flexor carpi radialis (FCR) is also present.
- Low-level tetraplegia (IC.G6 to IC.G9). From IC.G6 the finger extensors are present and the TR is present bilaterally (TR+). In low-level tetraplegia, FSTUL is not specific to this group but rather to surgery of the peripheral paralytic hand like in ulnar-median palsy. We will not discuss low-level tetraplegia in this article.

Table 2
International classification modified by Allieu. High- and mid-level tetraplegia.

Group	M4 (BMRC) muscles	Transferable muscles	Triceps
IC 0	No muscle below the elbow		–
High-level tetraplegia			
IC 1	BR	BR	–
IC 2	BR + ECRL	BR	–
Mid-level tetraplegia			
IC 3	BR + ECRL + ECRB	BR, ECRL	+/–
IC 4	BR + ECRL + ECRB + PT	BR, ECRL	+/–
IC 5	BR + ECRL + ECRB + PT + FCR	BR, ECRL	+/–
Low-level tetraplegia			
IC 6	Finger extensors	Multiple transfers possible Surgery not specific to tetraplegia	T+
IC 7	Thumb extensors		
IC 8	Partial digital flexors		
IC 9	Lack only intrinsics		
IC 10			Exceptions
Triceps Tr+			Tr–
Triceps Tr+			Tr–
Pectoralis Major PM+			PM–
Spasticity SP+			SP–
Harmful SP + H		Useful SP + U	

BMRC: British Medical Research Council; BR: brachioradialis; *ECRL*: extensor carpi radialis longus; *ECRB*: extensor carpi radialis brevis; *PT*: pronator teres; *FCR*: flexor carpi radialis; *Tr*: triceps brachii; *PM*: pectoralis major; *SP*: spasticity.

FSTUL applies to Group IIA for high-level tetraplegia and IIB for mid-level tetraplegia in Hentz classification [16–18]. This classification is based on the functions to be restored (Table 3).

- The triceps brachii-like in the IC is considered separately because of the extent of its innervation and denoted Tr+ or Tr–. We also note the pectoralis major (PM) as being PM+ or PM–. The PM stabilizes the shoulder anteriorly with the anterior part of the deltoid. The shoulder affects the orientation of the upper limb in space, allowing us to use several tricks to compensate for elbow extension deficit.
- Sensory evaluation: we think that sensation in the hand determines the quality of the results, but its absence should not be a contraindication for surgery.
- Soon after the Giens IC meeting, we added the absence (noted SP–) or presence of spasticity or muscle tone (noted SP+). Spasticity is moderate in most cases but it can be significant and harmful (*noted Sp + H*) and must be treated with precaution in some cases with botulinum toxin or surgically by flexor lengthening when there is flexor contracture [19]. When spasticity is significant and cannot be treated, it is a contraindication for FSTUL. But, in some cases, this spasticity can be useful (noted Sp + U) when the muscles innervated by the medullary SLS activity allow some grasp and pinch grip motions thanks to slight flexor spasticity and when the thumb is well positioned

Table 3
Hentz classification.

Group I	Non-surgical
Group II A	Re-establish "automatic" hand with active wrist and elbow extension
Group II B	Re-establish active finger flexion
Group III	Re-establish fine function by multiple transfers

Table 4
Paralyzed hand muscle assessment (Y. Allieu): table to fill out for each patient.

	Sp –	Sp+	
		Useful (SpU) *muscle tone*	Harmful (SpH)
FD			
FDS			
FDP			
FPL			
Thumb intrinsics			
Finger intrinsics			

Sp: spasticity; *SpU*: useful spasticity; *SpH*: harmful spasticity; *FD*: flexor digitorum; *FDP*: flexor digitorum profundus; *FDS*: flexor digitorum superficialis; *FPL*: flexor pollicis longus.

due to the tone of its intrinsic muscles. Some spasms are useful for the patient. It is important in FSTUL to take into consideration the activity and extent of the SLS and the types of paralyzed hand muscles. If the spinal cord injury is extended lengthwise, all the hand muscles are denervated with LMN damage (SP–) or, if the spinal cord injury is narrow with an extended SLS, all the hand muscles have central palsy with variable muscle tone and spasticity (SP+): moderate (which can be overlooked), harmful (SP + H) or useful (SP + U). Muscle tone is also denoted SP + U.

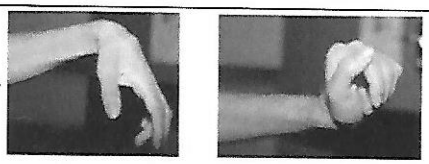
Besides these two types of tetraplegic medullary spine (extended spinal cord injury lengthwise without SLS and narrow spinal cord injury with large SLS), Coulet et al. [20] described an intermediary and heterogeneous type of SLS in mosaic: some hand muscles are more or less denervated (SP–) and others are not, presenting central palsy. Hence, while the finger flexors are always innervated (SP + U or SP + H), the intrinsic muscles which may or may not be innervated. We supplemented our classification based on the upper level of the LS with an assessment of hand muscles based on the type of muscle paralysis (Table 4). Tetraplegia cannot be defined solely by its level. Within the same level, there can be differences depending on the type of hand paralysis (Table 5A–C). Moreover, in the same patient, the tetraplegia can be asymmetric with a difference between the two hands according to the type of paralyzed muscles and depending on the LS or on the SLS (Tables 5D and 6).

4. What?

The aim of FSTUL is to reconstruct active elbow extension and hand gripping [21].

Table 5
Three different mid-level tetraplegias with the corresponding table filled out. Mid-level tetraplegia (I.C.L. Group 4) (A). (B) Mid-level tetraplegia (I.C.L. Group 3). (C) Mid-level tetraplegia (I.C.L. Group 3) (right and left sides).

A.



	Sp–	Sp +	
		Useful (SpU) *muscle tone*	Harmful (SpH)
FD			
FDS		X	
FDP			
FPL		X	
Thumb intrinsics		X	
Finger intrinsics		X	

B.

	Sp–	Sp+	
		Useful (SpU)	Harmful (SpH)
FD			
FDS			X
FDP			X
FPL		X	
Thumb intrinsics		X	
Finger intrinsics		X	

C.

	Sp–	Sp+	
		Useful (SpU)	Harmful (SpH)
FD			
FDS			X
FDP			X
FPL	X		
Thumb intrinsics	X		
Finger intrinsics	X		

Sp: spasticity; *SpU*: useful spasticity; *SpH*: harmful spasticity; *FD*: flexor digitorum; *FDP*: flexor digitorum profundus; *FDS*: flexor digitorum superficialis; *FPL*: flexor pollicis longus

Table 6
Asymmetric mid-level tetraplegia (IC.G3) where right and left hands have different paralyzed hand muscles: table filled out for each hand.

Right Mid-Level G 3	Sp−	Sp +	
		Useful (SpU)	Harmful (SpH)
FD FDS FDP			X X
FPL		X	
Thumb intrinsics		X	
Finger intrinsics		X	

Left Mid-Level G 3	Sp−	Sp +	
		Useful (SpU)	Harmful (SpH)
FD FDS FDP	X X		
FPL	X		
Thumb intrinsics	X		
Finger intrinsics	X		

Sp: spasticity; *SpU*: useful spasticity; *SpH*: harmful spasticity; *FD*: flexor digitorum; *FDP*: flexor digitorum profundus; *FDS*: flexor digitorum superficialis; *FPL*: flexor pollicis longus

4.1. Reconstruction of active elbow extension

Reconstruction of active elbow extension is needed bilaterally in high-level tetraplegia and unilaterally or bilaterally in mid-level tetraplegia. Active elbow extension is of prime importance and largely determines the functional autonomy of the tetraplegic patient. The aim is to orientate the hand in space and especially, to extend the range of gripping above the head. Reconstruction of active elbow extension stabilizes the elbow and concentrates the BR's elbow flexion action distally, allowing the BR to be used to restore hand gripping. Hence restoring active elbow extension must be the first step and generally precedes hand grip reconstruction. This is also a procedure whose consistent functional results help the patient to gain confidence for the rest of the treatment. The posterior deltoid (PD) and the biceps brachii (BB) are the two muscles that can be transferred to the paralyzed Tr to restore active elbow extension.

4.1.1. From PD according to Möberg to BB transfer according to Zancolli [22]

My indications have evolved since my first report in 1985 on 21 cases of active elbow extension restoration by PD to TR transfer [23]. For my first patients, I used the PD transfer. The drawback of Möberg's technique is the lack of strength in the last degrees of extension with limited range of motion. These drawbacks, which Möberg acknowledged, were reported by multiple authors. Our biomechanical studies on elbow extension reanimation after PD to TR transfer confirmed and analyzed these drawbacks [24]. Hence, several technical modifications were made relative to the intermediary tendon and its junctions with the PD. I also modified Möberg's technique: to join the PD to the TR, I used an artificial inextensible tendon wrapped in fascia lata (Fig. 2).

Later, I also used the BB to Tr transfer according to Zancolli (but by a medial approach – the lateral one had been abandoned) in highest level tetraplegia because using the PD can destabilize the shoulder when the PM and the anterior deltoid are absent or insufficient (Fig. 3). I continued to use the PD when the shoulder was stable anteriorly [25,26].

We have used BB to TR transfer for 15 years in all patients. The BB-to-TR transfer technique is easier to perform than PD-to-Tr transfer. The BB-to-TR necessitates only one suture instead of two sutures to the intermediary tendon joining the PD to Tr. The rehabilitation is simpler, and the results are more consistent. The drawback of this technique is loss of strength in elbow flexion (35% on an average) but in fact this loss is not detrimental to the tetraplegic patient's activities [27–29] (Fig. 4).

4.1.2. Nerve transfers

Recently, according to Bertelli, various nerve transfer techniques are relevant and may be promising in FSTUL. For Tr: transfer of the nerve to teres minor to that of the long head of the Tr, transfer of the nerve to brachialis to that of the Tr [30,31]. The first nerve transfer in FSTUL was reported by Benassy and Robart [32] in 1960 (musculocutaneous nerve to median nerve transfer to reanimate finger flexion). This followed only by Krasuki and Kiwerski [33] in 1991; the other authors used tendon transfers for this function (BR or ECRL transfer to flexor digitorum profundus - FDP). The relevance of nerve transfers and their indications compared to tendon transfers in tetraplegia will only be specified after a sufficiently long follow-up with several surgeons contributing their cases. It also depends on the results of nerve repair, which are not consistent and can take several months, contrary to tendon transfers whose results are consistent and rapidly noticeable by the tetraplegic patient who needs rapid improvement.

4.1.3. Functional results

Reconstruction of active elbow extension restores hand positioning above the head and can improve activities of daily living, such as wheelchair propulsion and bladder percussion. Although tetraplegic patients often hope for postoperative improvement in body transfer, the surgeon should not promise

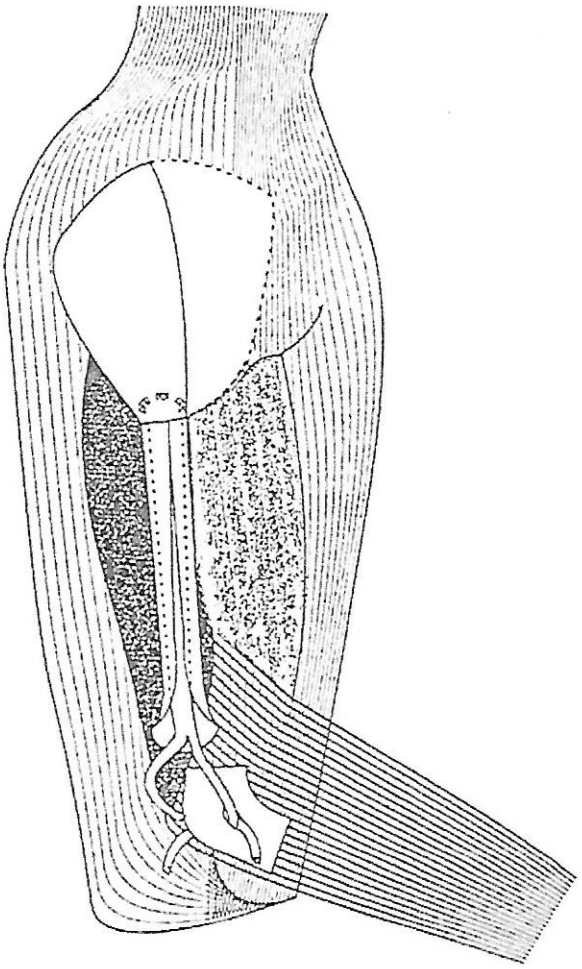


Fig. 2. Posterior deltoid to triceps brachii transfer: personal technique (that is no longer used) with an inextensible artificial tendon wrapped in fascia lata.

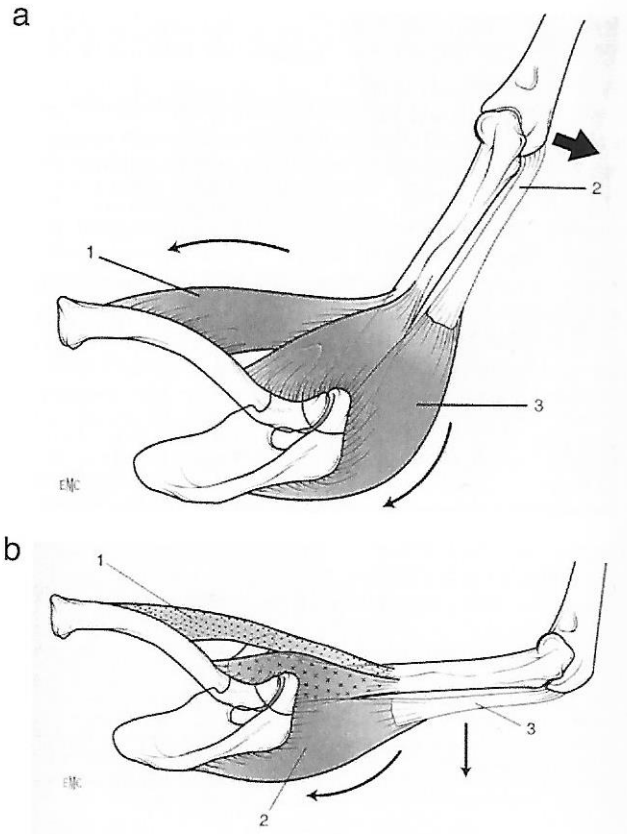


Fig. 3. Posterior deltoid to triceps brachii transfer when the pectoralis major and anterior deltoid are present, counteracting shoulder extension initiated by the transfer (A) and when the pectoralis major and anterior deltoid are absent (B) in high-level tetraplegia. *1*: pectoralis major; *2*: posterior deltoid; *3*: artificial tendon.

this because it does not always occur after elbow reconstruction. The surgeon should only inform the patient of the functional benefits he or she can surely achieve. The Baltimore Therapeutic Equipment (BTE) Work Simulator is useful for assessing and rehabilitating the upper limb. With the BTE, we analyzed the role of the triceps brachii when driving a car [34]. Driving without the triceps is possible, but active elbow extension allows better trajectory adjustment and improves driving ability. The BTE also lets the patient evaluate his movements depending on the situation. Driving a car is particularly important for these patients, if it is taught during the rehabilitation program, the patient may wish to undergo surgery more readily. We have also analyzed the role of active elbow extension in sports [35]. Active elbow extension increases the possibility of participating in sports, however its importance varies. Ironically, tetraplegia and sports are closely related. Not only are 33% of tetraplegia cases caused by sports injuries, but young tetraplegic patients are participating and competing in sports, like in the International Paralympics Games for athletes with disabilities. Practicing a sport during the hospitalization phase seems to improve the health and well-being of these patients. Swimming provides a benefit in these patients but requires bilateral elbow extension (Fig. 4D). After bilateral reconstruction of elbow extension, even high-level tetraplegic patients can swim and even deep-sea dive with a specialized team. Below the water surface, they can discover a new universe in which their handicap is far less of a hindrance. Surgeons must keep in mind that some tetraplegic patients (usually the younger ones) may want to compete and not merely participate in a particular sport. The competitions for athletes with a disability require a classification system. In tetraplegic patients who excel at a particular sport, postoperative improvement in the quality of daily life may be secondary to their athletic achievements. For example, a patient without triceps activity, who became a champion table tennis player in his classification by using shoulder movements to adapt to his handicap, feared that he might lose his sports classification because he would have to change his sport category after active elbow extension reconstruction. Hence he refused our suggested surgery. This case demonstrates the importance of operating before adaptation sets in.

4.2. Reconstruction of hand gripping

In FSTUL there are two types of reconstruction of hand gripping: the key pinch (or lateral pinch) grip and the power grip by finger flexion for a stronger grasp. The most effective and simple grip is the key pinch grip (KG) where the thumb squeezes against the lateral middle phalanx of the index finger. The KG is the type of grip used the most in daily activities [36], including bladder self-catheterization.

4.2.1. Tetraplegia level

The possibilities of hand grip reconstruction depend on the level of tetraplegia defining the number of remaining transferable muscles. The method for grip reconstruction must take into

Fig. 4. Results of biceps brachii to triceps brachii bilateral transfer: raising the upper limb (A), elevating the body from the wheelchair (B); elevating a lower limb (left) with the opposite upper limb (C), swimming (D). In Fig. 4C the patient has enough flexion strength to lift his leg for transfers.

consideration the presence or absence of the SLS and the type of hand muscle paralysis (peripheral or central palsy with muscular tone and more or less spasticity).

- High-level tetraplegia (IC.G1, IC.G2): Functional surgery in patients with high-level tetraplegia is characterized by only one transferable muscle, the BR.
- In IC.G1, where there is no extensor carpi radialis (ECR), the BR is transferred to the ECR so as to restore wrist extension and which then allows *passive KG* activated by active wrist extension.
- In IC.G2 when wrist extension due to ECRL is sufficient (graded at minimum of 4) we transfer the BR to the FPL. This *active KG* does not depend on wrist extension. If radial deviation of the wrist due to the action of the ECRL is too large, we carry out ECRB plication.
- Mid-level tetraplegia (IC.G3, IC.G4, IC.G5): In mid-level tetraplegia, strong wrist extension is due to the presence of the ECRL and ECRB muscles. There are two transferable muscles, the BR and the ECRL, with the ECRB providing wrist extension. With two transferable muscles, it is possible to construct not only an active KG but also a power grip.
- In IC.G4 at present we prefer not to transfer the PT so as not to modify pronation-supination. We continue to transfer only the BR and the ECRL. We confirm that the ECRB has ≥M4 strength and confers strong wrist extension.
- In IC.G5, the FCR is never used so as not to eliminate active wrist flexion, which allows hand opening due to finger extensor tenodesis.

Clinically, IC.G2 (high level tetraplegia) with only the ECRL and IC.G3 (mid-level tetraplegia) with the ECRL and ECRB can be differentiated by a groove separating the muscle bellies visible on the forearm in IC.G3 (Fig. 5).

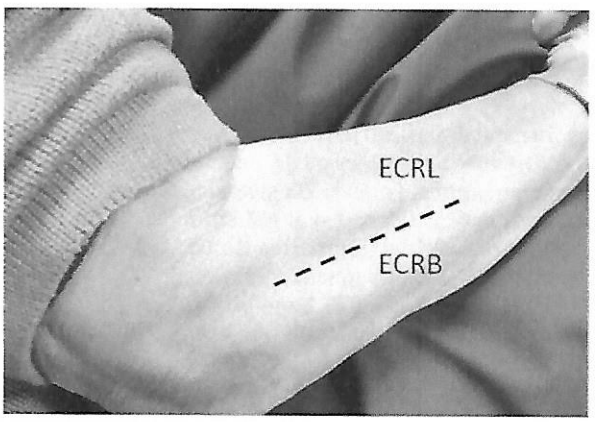


Fig. 5. In IC.G3, the groove visible between the ECRB and ECRL muscle bellies.

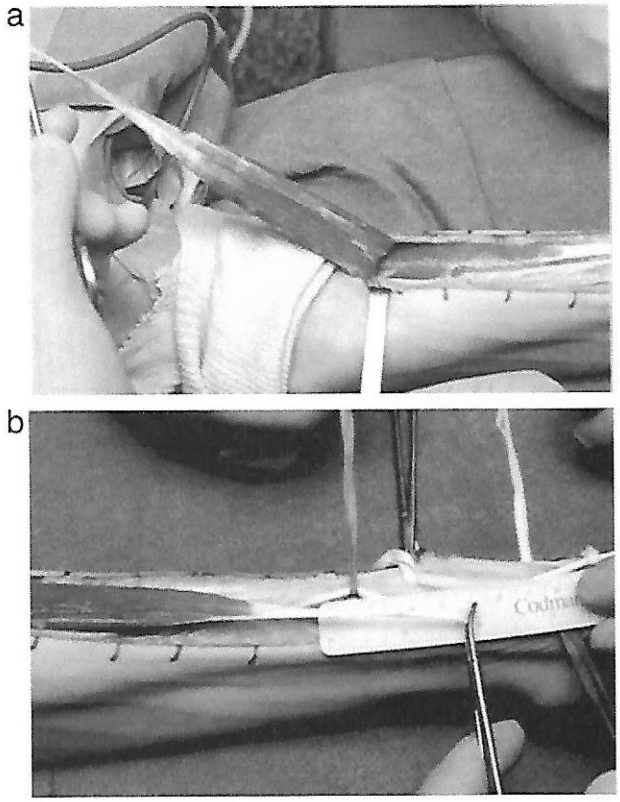


Fig. 6. Complete BR release (A) and lengthening of its excursion obtained before its transfer to the flexor pollicis longus tendon (B).

4.2.2. Passive KG construction

Described by Möberg in 1975, who laid the foundations of FSTUL, the passive KG is a thumb pad to lateral aspect of index finger grip activated by active wrist extension with flexor pollicis longus tenodesis on the radius.

At first, wrist extension is assured by transfer of the BR to the ECR. The BR is transferred to the ECR after completely releasing the body of the muscle from its fascial envelope and intermuscular attachment to the level of its neurovascular pedicle, which lies just distal to the elbow crease. I would like to stress the importance of this surgical step in FSTUL. Freeing the muscle from its attachments is essential. It must be pursued until the muscle can be extended by at least 3 cm to 5 cm by distal traction on its tendon (Fig. 6).

Secondly, we construct a KG by FPL tenodesis on the radius. KG construction according to Möberg in 1975 was modified by several authors. We have also modified this technique so as to improve the opening and closing adjustments by "mirror tenodesis" [37]. The FPL and EPL are passed in opposite directions through a tunnel drilled transversely in the radius. The direction of the tunnel is very important. It must pass from the ulnar border of the radius on its palmar aspect to the dorsolateral border of the radius, beside the first dorsal compartment. The two tendons are passed through in opposite directions, the FPL from palmar to dorsal, the EPL from dorsal to palmar. The two tendons are sutured to each other after determining their relative tension by tightening them until the thumb position is satisfactory (Fig. 7).

As a general rule, passive KG construction requires a two-stage procedure, wrist extension reanimation first and KG construction second. Between these two stages, the patient undergoes wrist extension rehabilitation.

4.2.3. Active KG construction

The BR is released and transferred to the FPL. This transfer is performed to obtain the correct KG position. Regulation of the tension is subjective and varies between authors, which explains the variability of the results. Personally I regulate the tension so that the pulp of the thumb remains lightly in contact with the middle phalanx of the index finger, while placing the elbow in 45° flexion and the wrist in 10° flexion. Recent research by Lieber and Friden on muscle microanatomy and physiology specifies the exact tension of this transfer [38] but this cannot be applied easily in our

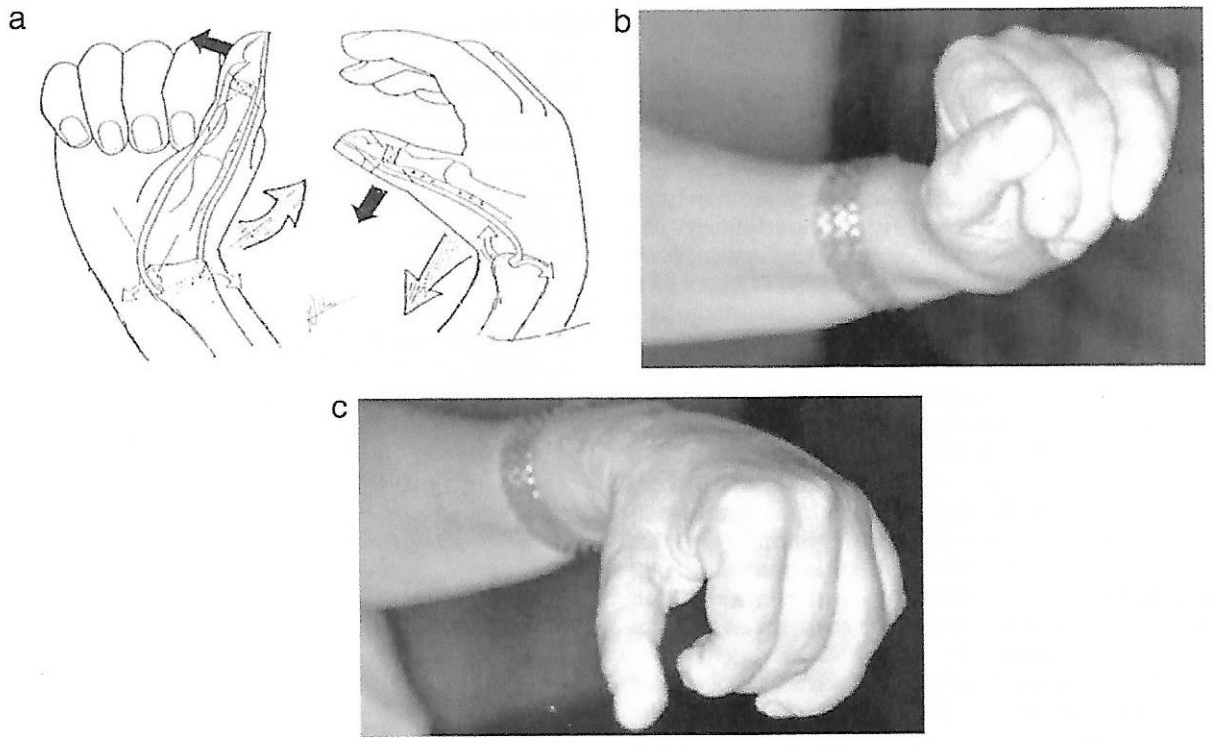


Fig. 7. Drawing of the mirror tenodesis technique (Allieu) (A), which results in key pinch grip closing (B) and opening (C).

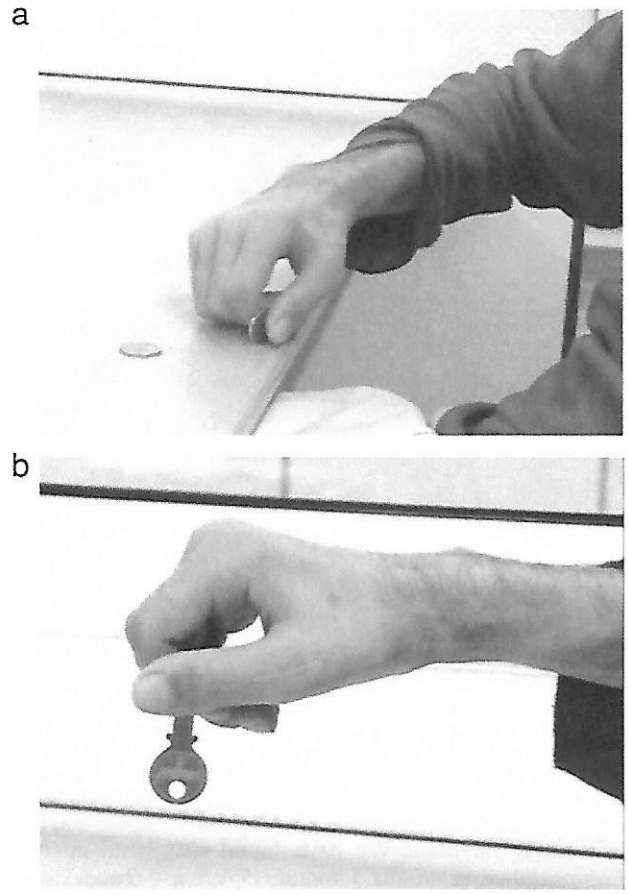


Fig. 8. Active key pinch grip. Key pinch grip is possible without wrist extension. Anterior (A) and medial (B) views.

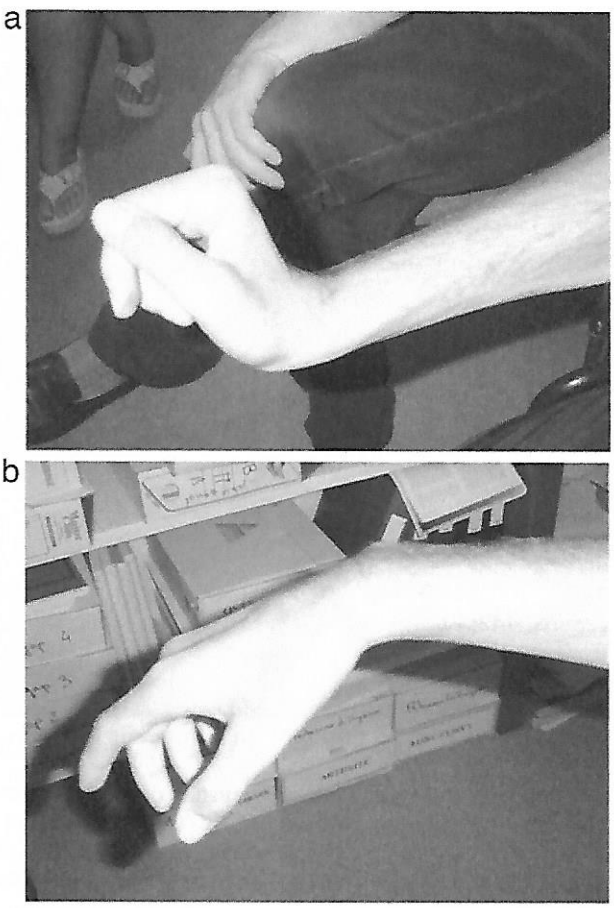


Fig. 9. Good spontaneous positioning for key pinch grip: closing in wrist extension (A), opening in wrist flexion (B).

clinical practice. The strength of active KG (on average 2 kg) is better than passive KG (on average 1 kg). These results can vary greatly from one study to another and even within a study, depending on multiple factors [39]. In active KG, the patient can use his or her KG without wrist extension due to BR contraction, contrary to passive KG (Fig. 8).

When the thumb intrinsic muscles are paralyzed, reanimation of the FPL by BR transfer results in a thumb IP flexion (intrinsic minus thumb) and must be corrected by tenodesis or IP arthrodesis.

4.2.4. Choice of KG construction

The surgeon must consider several factors before reconstructing the KG, which is complex and must be customized to each patient:

- The thumb's position in wrist extension and wrist flexion, which depends on the presence or absence of a SLS
- The thumb column's stability
- The position of the radial side of the middle phalanx of the index finger on which the thumb positions itself during KG closing.

4.2.4.1. Thumb positioning. If the thumb intrinsic muscles are included in the SLS with muscle tone, the thumb can be spontaneously well positioned (Fig. 9); if not, the thumb must be positioned correctly by TM joint arthrodesis or by double tenodesis:

- In TM arthrodesis, the TM joint is fixed in the KG position, with the thumb being in approximately 40° abduction and 40° antepulsion. This arthrodesis corrects the thumb's incorrect position in supination in the palmar plane and TM instability. However, this arthrodesis stiffens the hand and limits first web opening [40].
- Double tenodesis leaves the TM mobile but with a weaker KG than after TM arthrodesis. Moreover the technique is more complex. The thumb must be well positioned not only during KG closing but also during KG opening (Fig. 10):
- Thumb positioning in KG closing: we perform an opponens tenodesis as described by Zancolli [41] by passing one slip of the APL or the EPL around the FCR and then suturing it to itself. Tenodesis is activated by wrist extension to place the thumb in front of the plane of the palm, which positions the thumb in opposition during KG closing.
- Thumb positioning in KG opening: The APL is fixed on the dorsal side of the wrist to open the first web space. To correct its retropulsion effect during pinch opening, the EPL is translocated and fixed at the distal insertion of the BR.
- The active KG strength is better when the thumb is positioned by TM arthrodesis (on average 2.6 kg vs. 1 kg without arthrodesis). The amplitude of the passive KG opening (thumb pulp to index pulp) is better when the TM is left mobile (54 mm vs. 25 mm with arthrodesis). Thumb positioning without arthrodesis has the advantage of maintaining a supple hand. If we operate on both upper limbs, two different KGs can be constructed with arthrodesis on one hand and double tenodesis on the other.

4.2.4.2. Stabilization of thumb joints. The IP joint is stabilized by tenodesis of the hemi-FPL to EPL called "the New Zealand

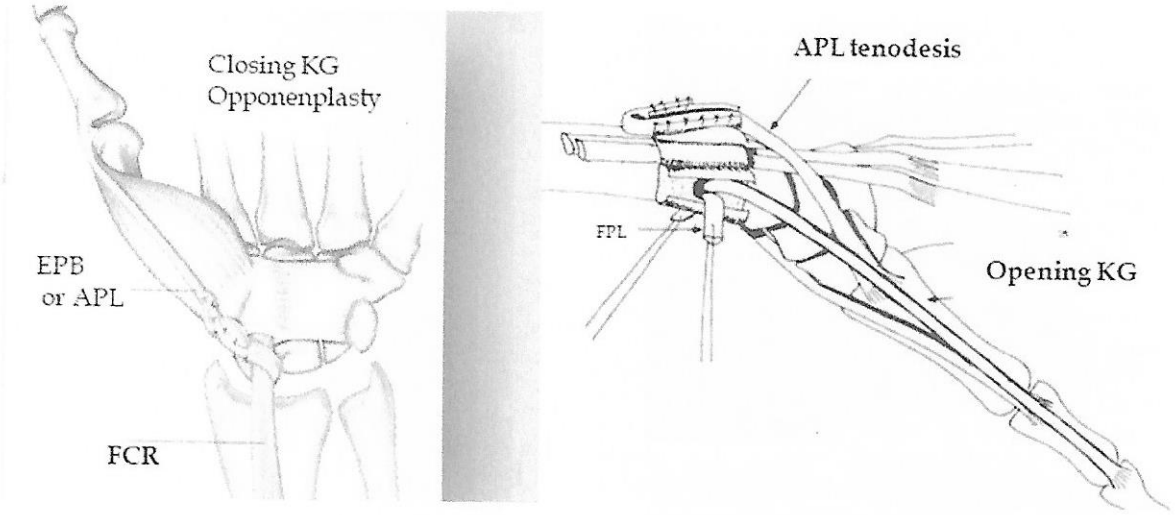


Fig. 10. Double tenodesis. Anterior view (A), lateral view (B). *APL*: abductor pollicis longus; *EPB*: extensor pollicis brevis; *FPL*: flexor pollicis longus; *FCR*: flexor carpi radialis.

procedure" [42] which maintains suppleness, contrary to IP arthrodesis. If the MCP joint is too lax (more than 45°), it is stabilized by tenodesis of the EPB to the dorsum of the thumb metacarpal to avoid MCP hyperflexion. If the MCP joint has considerable laxity (more than 90°), an arthrodesis is performed.

4.2.4.3. Index finger position in KG. The results of the KG construction depend not only on the thumb but also on the position of the index finger when the wrist is dorsiflexed. The thumb must position itself on the radial side of the middle phalanx of the index finger:

- If the MCP joint of the index is too flexed (more than 60°), the thumb will be relatively too long, and its pulp cannot contact the middle phalanx of the index finger. This can be corrected by shortening arthrodesis of the thumb IP joint or by index flexor tendon lengthening.
- On the contrary, if the index finger is too straight in wrist extension, the thumb passes volar to the index. In this case, we do not like to fix the index in flexion but prefer to keep the hand supple and teach the patient to passively flex his index and finger MCPs before gripping by using the "rolling technique" described by Möberg. I dislike Zancolli's lasso here, which stiffens the hand.

In KG construction, we previously used cervical epidural anesthesia that provided selective sensory block and left the patient conscious to move his wrist and see the result of the KG allowing for better adjustment [43]. But we no longer use it because this technique is complex and cannot be generalized. Today, WALANT surgery [44] can allow KG adjustment with the advantage of no bleeding.

4.2.5. Power grip construction

In mid-level tetraplegia with two transferable muscles (BR and ECRL), it is possible to construct not only an active KG by transferring the BR to the FPL but also a power grip [45]. Hand closing is active by transfer of the ECRL to the FDP. Hand opening is passive by extensor tenodesis.

4.2.5.1. Finger flexion. Mid-level tetraplegia is classically defined by the presence of strong wrist extension due to the two ECR muscles being graded as MRC 4. However, strong wrist extension may be due to the combined action of the two ECR muscles where the ECRB graded below 3 but the ECRL is strong. In this case, transfer of the ECRL to the FDP is contraindicated. When the ECR testing is not conclusive and no obvious groove is present, evaluating the two radial wrist extensors is always a problem; thus, one must be cautious before transferring the ECRL. In this case, we transfer the ECRL only when the PT is not totally paralyzed. If it is, we use a selective ECRL block proximal to the lateral epicondyle of the humerus to test the ECRB and achieve strong wrist extension.

4.2.5.2. Finger extension. We have found that hand opening is always passive even in IC G4 and IC G5. We use tenodesis of the extensors on the dorsal annular ligament placed under tension during wrist flexion to achieve passive finger-palm opening [46].

4.2.5.3. Intrinsic muscle deficit. When the intrinsic muscles are denervated, reanimation of the extrinsic muscles results in an extrinsic-intrinsic imbalance and an intrinsic minus hand (Fig. 11). The treatment objective is to stabilize the MCPs in flexion during active finger flexion and the IPs in extension during passive opening of the hand. We use the Zancolli lasso technique in this case [47,48].

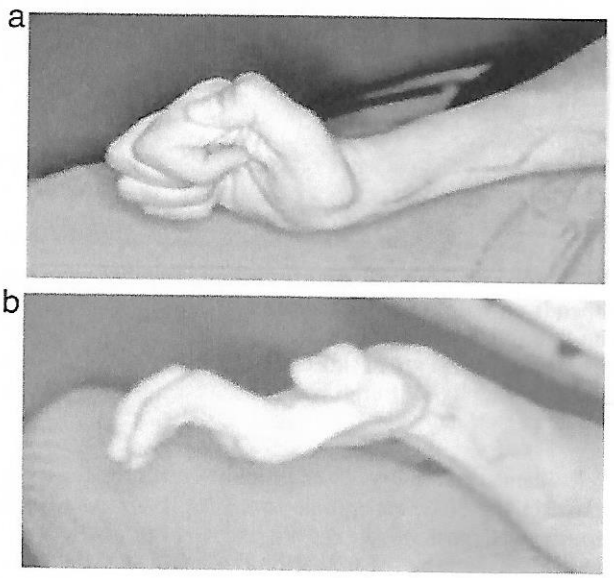


Fig. 11. Postoperative intrinsic minus hand after extensor carpi radialis longus to flexor digitorum profundus transfer and brachioradialis to flexor pollicis longus transfer: closing in writs extension (A), opening in wrist flexion (B).

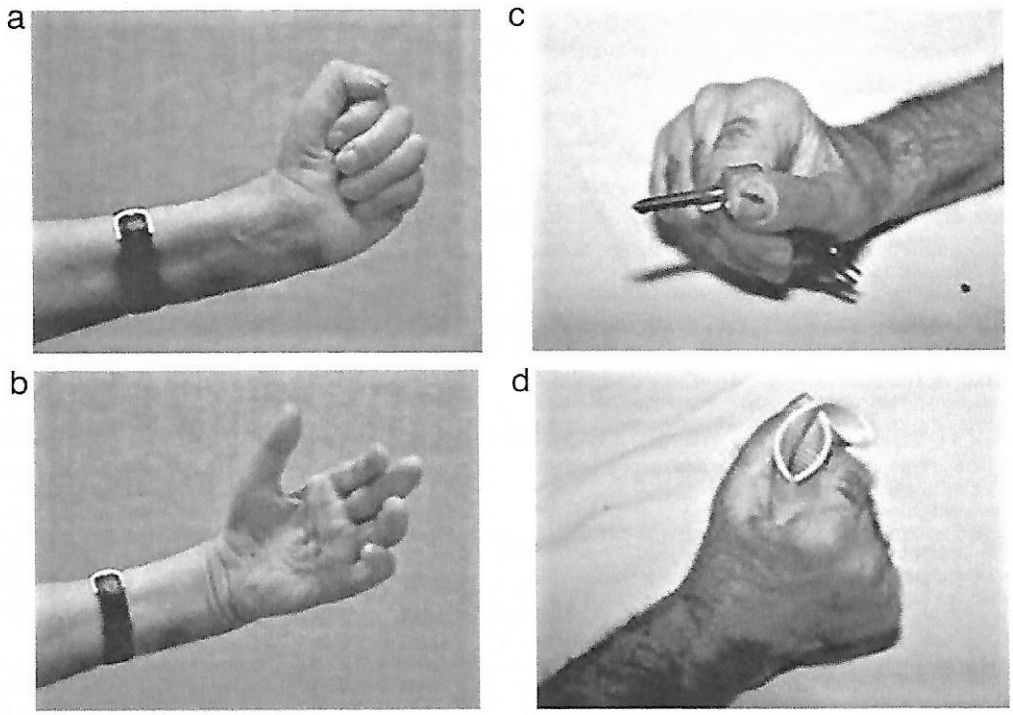


Fig. 12. Active key pinch grip and power grip in a mid-level tetraplegia patient classified as IC.G3 after extensor carpi radialis longus to flexor digitorum profundus transfer and brachioradialis to flexor pollicis longus transfer (active closing), tenodesis of the extensors on the extensor retinaculum (passive opening), and Zancolli lasso procedure: closing the fist (A); opening the hand (B), active key pinch grip (C), power grip (D).

4.2.5.4. Timing of surgery. Generally, the opening procedure is performed first followed 2 months later by the closing procedure [49,50]. Personally, I prefer to perform the closing procedure first. Reanimation of the finger flexors by transfer of the ECRL to the FDP is carried out in association with an active KG by transferring the BR to the FPL. This choice is better psychologically for the patient who can see the resulting finger flexion and active KG (Fig. 12). Moreover, in our experience, the patient sometimes does not wish to undergo the opening procedure.

When the possibility exists of reconstructing active KG and a power grip in both hands, we first reconstruct active KG only in one hand and secondly the power grip combined with active KG in the other hand. Our experience shows that in most cases, the patient prefers KG only. This was the case in a mid-level tetraplegic patient who was going to travel all around the world and had a specific need: to be able to insert a suppository by himself. Reconstruction of active KG in one hand allowed him to do this and the patient refused all other procedures.

When the IPs are too flexed due to flexor spasticity and when extension is not possible because of the digital extensor mechanism is elongated, one must have recourse to KG only and no power grip. Power grip reconstruction comes with the risk of a stiff hand, which is a problem for the patient, especially for young patients who sometimes prefer having a supple hand. According to Ejeskar [51], we must take into consideration the important role of the hand in human contact. This function is often neglected but is an important factor and may conflict with grip reconstruction.

5. Conclusion

My personal experience has shown me the prime importance of a precise surgical indication and intraoperative adjustment of transfer tension. Each case is different. FSTUL should be considered as the surgical rehabilitation of a tetraplegic patient and not a reconstructive surgery for tetraplegia. It is vital to take into consideration the patients' wishes and not all the surgical possibilities. At present, FSTUL is a "winning surgery" for a well-informed patient with a realistic goal. Unfortunately, it is not well known in the medical field. Patients may be unaware of FSTUL as they often expect miracles and are seduced by over-publicized procedures that have little proof of their efficiency. Rehabilitation (physical therapy, occupational therapy) is of great importance.

The goal of FSTUL is rapid social integration of the patient. To achieve this, when it is possible and safe in the centers where we work, surgery time must be reduced as well as the stay in the rehabilitation centers. We are in favor of one-stage active elbow extension restoration and grip restoration by KG (passive or active) as we published in 2001 [52]. We think that the concept of a one-stage procedure in FSTUL according to Friden [53] must be applied in all cases when feasible. FSTUL is in constant evolution [54,55] and continues to be perfected. Fundamental studies aim to standardize and improve the efficiency of tendon transfers, but they cannot yet be applied clinically in all the centers. Nerve transfer could be an answer to FSTUL in some cases. FSTUL remains a palliative surgery to treat the consequences of spinal cord injuries; it is not a curative surgery. The future lies in the treatment of spinal cord injuries.

Disclosure of interest

The author declares that he has no competing interest.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Ethical approval

The study is in accordance with the ethical standards of the institutional ethics committee and with the 1964 Helsinki declaration and its later amendments.

Author contributions

All authors attest that they meet the current International Committee of Medical Journal Editors (ICMJE) criteria for Authorship.

References

[1] Allieu Y, Benichou M, Teissier J, Desbonnet P, Lussiez B. La réanimation du membre supérieur du tétraplégique par transferts tendineux. Chirurgie 1986;112:736–42.
[2] Allieu Y. Chirurgie fonctionnelle du membre supérieur du tétraplégique. EMC Tech Chir – Orthop – Traumatol 2015;1–16 [Article 44-460].
[3] Allieu Y. Functional surgery of the upper limb in tetraplegia. In: Urbaniak JR, editor. Hand surgery worldwide. Athens: Konstantaras Medical Publications; 2011. p. 377–81.
[4] Allieu Y. General indications for functional surgery of the hand in tetraplegic patients. Hand Clin 2002;18:413–21.
[5] Möberg E. Surgical treatment for absent single-hand grip and elbow extension in quadriplegia. Principles and preliminary experience. J Bone Joint Surg Am 1975;57:196–206.
[6] Möberg E. The upper limb in tetraplegia: a new approach to surgical rehabilitation. Stuttgart: Georg Thieme Publishers; 1978.
[7] Möberg E. Current treatment program using tendon surgery in tetraplegia. In: Hunter JM, Schneider LH, Mackin EJ, editors. Tendon surgery in the hand. St Louis: Mosby; 1987. p. 496–505.
[8] Möberg E. Traitement chirurgical des tétraplégies dues à des lésions médullaires cervicales hautes. In: Tubiana R, editor. Traité de chirurgie de la main. Paris: Masson; 1991.
[9] Giens' International classification (1984), McDowell CL, Möberg E, House JH. The second international conference on surgical rehabilitation of the upper limb in tetraplegia (quadriplegia). J Hand Surg Am 1986;11:604–8.
[10] Allieu Y, Benichou M, Ohanna F, Rabischong E, Benoit P. Functional Surgery of the upper limbs in tetraplegic patients. Current trends after 10 years of experience at the Propara Center. Rev Chir Orthop Reparatrice Appar Mot 1993;79:79–88.
[11] Coulet B, Boretto JG, Allieu Y, Fattal C, Laffont I, Chammas M. Pronating osteotomy of the radius for forearm supination contracture in high level tetraplegic patients: technique and results. J Bone Joint Surg Br 2010;92:828–34.
[12] Mulcahey MJ, Smith BT, Betz RR. Evaluation of the lower neuron integrity of upper extremity muscles in high level spinal cord injury. Spinal Cord 1999;37:585–91.
[13] Keith MW, Peckham PH, Thrope GB, Stroh KH, Smith B, et al. Implantable functional neuromuscular stimulation in the tetraplegic hand. J Hand Surg Am 1989;14:524–30.
[14] Keith MW, Hoyen H. Indications and future directions for upper limb neuroprostheses in tetraplegic patients: a review. Hand Clin 2002;18:519–28.
[15] Allieu Y, Benichou M, Ohanna F, Bousquet Ph., Chammas M. Classification chirurgicale du membre supérieur du tétraplégique. Ann Chir Plast Esthet 1993;38:180–6.
[16] Hentz VR, Brown M, Keoshian L. Upper limb reconstruction in quadriplegia: functional assessment and proposed treatment modifications. J Hand Surg 1983;8:119–31.
[17] Hentz VR. Surgical strategy: matching the patient with the procedure. Hand Clin 2002;18:503–18.
[18] Hentz VR, Leclercq C. Surgical rehabilitation of the upper limb in tetraplegia. London: WB Saunders; 2002.
[19] Treanor WJ, Möberg E, Buncke HJ. The hyperflexed seemingly useless tetraplegic hand: a method of surgical amelioration. Paraplegia 1992;30:457–66.
[20] Coulet B, Allieu Y, Chammas M. Injured metamere and functional surgery of the tetraplegic upper limb. Hand Clin 2002;18:399–412.
[21] Hamou C, Shah NR, DiPonio L, Curtin ML. Pinch and elbow extension restoration in people with tetraplegia: a systematic review of the literature. J Hand Surg Am 2009;34:692–9.
[22] Zancolli EA, Zancolli E. Tétraplégies traumatiques. In: Tubiana R, editor. Traité de chirurgie de la main. Masson; 1991.
[23] Allieu Y, Teissier J, Triki F, Mailhe D, Asencio G, Gomis R, et al. Réanimation de l'extension du coude chez le tétraplégique par transplantation du deltoïde postérieur: Etude de 21 cas. Rev Chir Orthop Reparatrice Appar Mot 1985;71:195–200.
[24] Rabischong E, Benoit P, Benichou M, Allieu Y. Length-tension relationship of the posterior deltoid to triceps transfer in C6 tetraplegic patients. Paraplegia 1993;31:33–9.
[25] Coulet B, Allieu Y, Chammas M, Ohanna F. Restoration of elbow extension in tetraplegic patients (98 limbs operated). J Hand Surg Am 2000;25(Suppl. 11):73.
[26] Allieu Y, Benichou M, Rabischong E, Chammas M. Restoration of elbow extension in tetraplegic. In: Vastamaki M, editor. Current trends in hand surgery. Amsterdam: Elsevier; 1995. p. 391–4.
[27] Kozin SH, D'Adessi L, Chafetz RS, Ashworth S, Mulcahey MJ. Biceps-to-triceps transfer for elbow extension in persons with tetraplegia. J Hand Surg Am 2010;35:968–75.
[28] Revol M, Briand E, Servant JM. Biceps-to-triceps transfer in tetraplegia. The medial route. J Hand Surg Br 1999;24:235–7.
[29] Médina J, Marcos-García A, Jiménez I, Muratore G, Méndez-Suárez JL. Biceps to triceps transfer: our experience and review of the literature. Hand (N Y) 2017;12:85–90.
[30] Bertelli JA, Ghizoni MF, Tacca CP. Transfer of the teres minor motor branch for triceps reinnervation in tetraplegia. J Neurosurg 2011;114:1457–60.
[31] Bertelli JA, Ghizoni MF. Nerve transfers for elbow and finger extension reconstruction in midcervical spinal cord injuries. J Neurosurg 2015;122:121–7.
[32] Bénassy J, Robart J. Un cas de transposition du nerf musculo-cutané sur le nerf médian. Ann Chir Plast 1966;11:187–9.
[33] Krasuski M, Kiwerski J. An analysis of the results of transferring the musculocutaneous nerve onto the median nerve in tetraplegics. Arch Orthop Trauma Surg 1991;111:32–3.
[34] Allieu Y. Evaluation of tetraplegic drivers' physical capacity with BTE work. In: E.F.S.S.H. meeting; 1994.
[35] Allieu Y, Benichou M, Ohanna F, Barbin JM, Benoit P. Tétraplégie et sport. Intérêts de la chirurgie fonctionnelle. In: Simon L, Pellissier J, Herisson Ch., editors. Actualités en rééducation fonctionnelle et réadaptation, 18e série. Issy-les-Moulineaux: Elsevier-Masson; 1993. p. 110–5.
[36] Allieu Y, Chammas M, Coulet B. Restauration chirurgicale d'une préhension par pince pollici-digitale dans les tétraplégies hautes. E-mémoires Acad Nat Chir 2002;1:29–32.
[37] Allieu Y, Coulet B, Chammas M. Functional surgery of the upper limb in high level tetraplegia. Part I. Tech Hand Upper Extrem Surg 2000;4:50–63.
[38] Lieber RL, Murray WM, Clark DL, Hentz VR, Fridén J. Biomechanical properties of the brachioradialis muscle: implications for surgical tendon transfer. J Hand Surg Am 2005;30:273–82.
[39] Smaby N, Johanson ME, Baker B, Kenney DE, Murray WM, Hentz VR. Identification of key pinch forces required to complete functional tasks. J Rehabil Res Dev 2004;41:215–24.
[40] House JH, Dahl JCA. One-stage key pinch and release with thumb carpal-metacarpal fusion in tetraplegia. J Hand Surg Am 1992;17:530–8.
[41] Zancolli EA. Surgery for the quadriplegic hand with active, strong wrist extension preserved. A study of 97 cases. Clin Orthop Relat Res 1975;112:101–13.
[42] Mohammed KD, Rothwell AG, Sinclair SW, Willems SM, Bean AR. Upper-limb surgery for tetraplegia. J Bone Joint Surg Br 1992;74:873–9.
[43] Deschodt J, Lubrano JF, Kassim M, Allieu Y. Cervical epidural anesthesia in tetraplegia. Hand Clin 2002;18:441–7.
[44] Lalonde DH. Conceptual origins, current practice and views of wide awake hand surgery. J Hand Surg Eur 2017;42:886–95.
[45] Allieu Y, Coulet B, Chammas M. Functional surgery of the upper limb in high level tetraplegia. Part II. Tech Hand Upper Extrem Surg 2000;4:64–8.
[46] Teissier J, Fattal Ch, Egon G. Strategy for improving hand opening in the tetraplegic upper limb. Hand Clin 2002;18:497–502.
[47] Zancolli EA. Correccion de la 'gara' digital por paralisis intrinseca. La operacion del 'lasso'. Acta Ortop Latinoam 1974;1:65.
[48] Zancolli EA. Structural and dynamic basis of hand surgery, 2nd ed., Philadelphia: JB Lippincott; 1979.
[49] House JH, Walsh T. Two-stage reconstruction of the tetraplegic hand. In: Strickland JW, editor. Master technique in orthopaedic surgery, the hand. Philadelphia: Lippincott Raven Publishers; 1988. p. 229–66.
[50] Zancolli EA. Midcervical tetraplegia with strong wrist extension: a two-stage synergistic reconstruction of the hand. Hand Clin 2002;18:481–95.
[51] Ejeskär A. Upper limb surgical rehabilitation in high-level tetraplegia. Hand Clin 1988;4:585–99.
[52] Allieu Y, Coulet B, Chammas M. Réanimation de l'extension active du coude et construction de la pince pouce-index en un temps chez le tétraplégique haut. Rev Chir Orthop Réparatrice Appar Mot 2001;87:2S72.
[53] Fridén J, Reinholdt C, Turcsányii I, Gohritz A. A single-stage operation for reconstruction of hand flexion, extension and intrinsic function in tetraplegia – the alphabet procedure. Tech Hand Up Extrem Surg 2011;15:230–5.
[54] Fattal C, Teissier J, Leclercq C, Revol M, Enjalbert M. Evolution de la prise en charge du membre supérieur tétraplégique depuis 50 ans. Ann Réadapt Med Phys 2003;46:144–55.
[55] Fridén J, Lieber RL. Reach out and grasp the opportunity: reconstructive hand surgery in tetraplegia. J Hand Surg Am 2019;44:343–53.