Surgical rehabilitation of upper limbs in tetraplegic patients: reconstruction of elbow extension, grasp and key-pinch function

Doktoral theses

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1. Introduction

Global incidence of spinal cord injury has been estimated as 70,000-560,000 new cases in the world per year. In Hungary it means an average of 250 new cases; one third of them has cervical spinal cord injury, resulting tetraplegia.

Patients suffering traumatic cervical spinal cord injury causes dramatic changes in patient's life: loss of hand and lower limb function, functional disturbances of defecation, urination, sexual function, muscle spasms, pain, decubitus and psychological changes. Reconstructive surgery of the upper extremities using tendon transfer and joint stabilizations or, more recently, nerve transfer, has become an accepted part of rehabilitation of patients with cervical spinal cord injury. Numerous case series have demonstrated that elbow extension, grasp and key-pinch can be restored reliably in tetraplegic patients.

1.1. International Classification (IC)

The first International Tetraplegia Upper Limb Classification system, based on sensibility and grade 4 muscles, was presented at the first International Tetraplegia Conference in Edinburgh, in 1978.

1.2. Active elbow extension

Several surgical techniques have been reported for the replacement of the lost elbow extension in tetraplegic patients. The most

established procedure is the posterior deltoid-to-triceps transfer. The surgical technique, postoperative rehabilitation regimen, and its duration, are not controversial. Fridén reported, that as much as 23 mm of the muscle tendon unit could slip during the immobilisation and rehabilitation period after deltoid-to-triceps tendon transfer using interposition tibialis tendon graft. The most vulnerable part of the graft-tendon unit, as evidenced by elongation of the tendon-to-tendon attachment, is the proximal muscle-tendon graft attachment.

1.3. The Alphabet procedure: reconstruction of grasp, key-pinch, intrinsic function and release in one-stage operation

In traditional two-stage tetraplegia upper limb reconstructive surgery, in the first phase, depending from the schools, either the flexor or the extensor function is reconstructed and only in the second phase can be the other missing function restored. The Alphabet operation is a combination of extensor and flexor phases, that will allow for active finger flexion and thumb flexion, passive proximal interphalangeal joint extension of the fingers and passive thumb extension in one stage. Improved suture technique and increased knowledge of tendon-to-tendon attachment mechanics provided the tendon transfer field with new and crucial information about possibilities to activate transferred muscle-tendon units immediately after operation.

1.4. Active thumb abduction

The EDM-to-APB tendon transfer gives a dynamic stability for CMC I joint, which has advantages over CMC I arthrodesis, provides the thumb with active adduction and abduction. Due to the small size and strength of EDM, it has not been considered a potential donor tendon in tetraplegia surgery until recently.

1.5. Review of a project to implement a tetraplegia upper extremity surgery service in Hungary from 2002 to 2016

In spite of the fact that the advantages of tetraplegia upper limb surgery are well-documented, in many countries tetraplegia upper extremity surgery is rarely performed, even in high developed countries. It seems logical to establish a national tetraplegia surgery service in every country, but multiple barriers can hinder the project, such as skepticism regarding the procedures, lack of social support of patient, inadequate motivation, negative attitudes toward this patient population.

2. Ojectives

The **overall aim** of this study was to improve upper limb function in tetraplegic patients: to reconstruct active elbow extension, grip, key-pinch and release and to make this reconstructive hand surgery available for all tetraplegic patients in Hungary.

Specific aims:

1. Reconstruction of active elbow extension

a. Shorter immobilization time

b. Improved donor muscle strength after completed treatment

c. Full joint range of motion

d. Mechanically stronger donor muscle-to-graft attachment

e. Mechanically stronger graft-to-insertion tendon attachment

f. Earlier loading/strength training

2. Reconstruction of grasp and key-pinch and release

a. Shorter immobilization time

b. Improved donor muscle strength after completed treatment

c. To reduce the risk of adhaesions

d. Full joint range of motion

e. To reduce the recovery period after surgical reconstruction of hand function

f. Development a 1-stage operation to replace the traditional 2-stage operation

3. Reconstruction of active thumb abduction

a. Improved control and positioning of thumb against index finger
b. Larger opening around object
c. Development of method that reduces need for arthrodesis of CMC I joint

4. Tetraplegia upper limb surgery in Hungary

Launching the upper limb reconstructive surgery for tetraplegic patients in Hungary.

3. Methods

3.1. Restoration of lost elbow extension using a modified surgical technique

Fifteen elbow extensors were reconstructed using the modified posterior deltoid-to-triceps transfer in 10 tetraplegic patients (two women and eight men, age 19–44 years). The mean age at injury was 26 years (16-37). The mechanisms of spinal cord injury were traumatic and resulted from traffic accident (n=4), diving (n=4), and a fall (n=2). The mean time between injury and reconstruction of active elbow extension was 6 years (1-21). The International Classification of the patients' upper limbs ranged from O:1 to OCu:5. Of the 15 upper limbs that had been assessed before transfers to restore elbow extension, 14 were grade 1 and one was grade 2. The strength grades of the posterior deltoid were 5 in 12 cases and 4 in two cases, and 3+ in one case. Follow-up times ranged from 5 to 19 months (mean 10). The distal deltoid tendon and the tendon graft were placed with an overlap of 7–8 cm and sutured side-to-side using 2/0 non-absorbable double running sutures. The distal stump

of the tendon graft was pulled through several holes made in the triceps tendon and finally passed through the bone channel and woven back and sutured to itself.

3.2. The Alphabet procedure: reconstruction of grasp, key-pinch, intrinsic function and release in one-stage operation

In three countries: in the Center for Advanced Reconstruction of Extremities / CARE and in the Department of Hand Surgery, Institute of Clinical Sciences, Sahlgrenska University Hospital, Göteborg, Sweden, in Szabolcs-Szatmár-Bereg County Hospitals and University Hospital, Nyíregyháza, Hungary and in Swiss Paraplegic Center, Nottwil, Department of Plastic, Reconstructive and Aesthetic Surgery, Switzerland on 25 patients (25 hands) was performed one-stage reconstructive surgery, providing grasp, key-pinch and release function between 2008 and 2010. Of the 25 patients, 7 patients were operated in the Orthopedic Department of Nyíregyháza, 14 patients were operated in Hand Surgery Department of Gothenburg and 4 patients were operated in Hand Surgery Department of Nottwill. 19 of 25 patients were men, 6 women, the average age of patients was 38 years (20-64 years), the time between injury and rcconstructive surgery was 14 years (1-31 years). Patients were categorized as IC group 4 (n = 21) and IC group 5 (n = 4). The pre-operative grasp and key-pinch strength were

0 MRC. The patient's follow-up time was 1.5 years (1-3 years) on average.

3.3. Restoration of active abduction of the thumb

Relocation of the minimum muscle extension to musculus abductor pollicis brevis (EDM-APB relocation)

In two countries (Department of Hand Surgery, Institute of Clinical Sciences, Sahlgrenska University Hospital, Gothenburg, Sweden and Orthopedic Department, Szabolcs-Szatmár-Bereg County Hospitals and University Hospital Nyíregyháza, Hungary) were performed EDM reconstruction in 15 patients with tetraplegia (7 women, 8 men) scheduled for tendon transfers were specifically screened for an EDM with muscle strength of at least Medical Research Council (MRC) grade 3 with movement against gravity. Mean age at the time of surgery was 43.9 (range 19–70) years, 4 were older than 60 years, of which 1 was aged 70 years. In 12 patients the cord disorder was caused by trauma due to motor vehicle or bike accidents, falls, or by diving into shallow water, and in 3 patients the cause was nontraumatic. Time from paralysis to surgery was 54.2 (SD 42.8) months. International Classification of patients' upper extremities ranged from OCu4 to OCu8, and one woman with a nontraumatic incomplete lesion was categorized as X (exceptional).

3.4. Review of a project to implement a tetraplegia upper extremity surgery service in Hungary from 2002 to 2016

We describe a 10-year project to implement a tetraplegia upper extremity surgery service in Hungary. The process of establishing a national tetraplegia hand surgery service is described, including a retrospective outcome study of upper extremity function after surgical reconstruction by this service. The latter comprised strength measurements of elbow extension, key pinch and grip, measurement of opening of the hand and patient-perceived outcomes according to House.

3.5. Method of statistical analysis

Data are expressed as mean +- standard error of mean (SEM). Student's t-test was used for comparison of pre-and postoperative results. Significance level was set to 0.05.

3.6. Postoperative rehabilitation

3.6.1. Restoration of lost elbow extension using a modified surgical technique

The arm was kept immobilised in a plaster cast for three weeks in a fully-extended elbow position. The patient had active wrist training and static contractions of the posterior deltoid muscle. At the end of the third week the cast was removed and an adjustable elbow angle

orthosis was applied, elbow flexion angle was increased by 15 a week. Exercises were started in the horizontal plane and an adjustable 0.5 kg weight on the wrist was used in limited range of motion to reinforce muscle strength after four weeks. At the seventh week first without, then with, an 0.5 kg weight, active elbow extension was allowed in the vertical plane as well.

3.6.2. Rehabilitation after Alphabet procedure

In the postoperative first day the plaster was removed and the patient is taught how to activate reconstructed muscle and passive tenodes 2-3 times a day. On the postoperative third day the patient can leave the hospital, equiped with written and oral instructions.

3.6.3. Rehabilitation after restoration of active abduction of the thumb

On the first postoperative days the goal is to learn how to activate the new donor muscle. After four weeks tast-oriented training is added to functional training.

4. Results

4.1. Restoration of lost elbow extension using a modified surgical technique

The mean (range) active elbow extension range of motion was 132 (120–145). In two cases, flexion contractures of the elbow joint were seen before operation despite preoperative treatment with serial casting to reduce extension deficit (30 and 40, respectively). Interestingly, both of these patients had no extension range of motion deficit six months after deltoid-to-triceps reconstruction. Elbow extension strength according to the British Medical Research Council grading system was MRC5 (n=3), MRC4+ (n=4), MRC4 (n=7), and MRC3 (n=1). All patients had full against gravity strength. The mean (SEM) strength for elbow extension in the horizontal shoulder plane was significantly greater than that on the vertical plane (10.4 (1.0) compared with 6.5 (1.2) Nm, $p<0.001$). Simple regression of strength compared with the elbow's position showed a significant linear correlation for both planes studied ($r2=0.64$ and 0.62 for the horizontal and vertical planes, respectively). The elbow extension strength increased gradually as the elbow flexion angle increased over 90. This was true for elbow extension when measured both in the horizontal and vertical planes. The steepest part of the slope for elbow extension strength was from 120□ to 135□ of flexion.

4.2. Results after Alphabet procedure

Twenty-five patients underwent the alphabet reconstruction procedure, a single stage operation, which can provide grasp, key-pinch and release function. After the reconstructive surgery the average grasp strength was 64 N (range 30-150 N) (SEM 0.69), the average key-pinch strength was 28.4 N (range 4-58 N) (SEM 0.36). Opening of the first web space was 5.8 cm (range 0-11 cm) (SEM 0.65). The significance level was p 0.05.

4.3. Results after restoration of active abduction of the thumb

All patients were re-examined at a mean of 38.4 (SD 22.7) months. They reported not only improved grip, but also a substantial improvement of opening of the hand, found they were able to perform many activities of daily life, and were able to eat and dress independently. After surgery, active thumb-index opening significantly increased from 2.5 (SEM 1.0) cm preoperatively to 9.0 (SEM 0.8) cm ($p < 0.001$). Nine of the 15 patients who had no active opening of the first web space (preoperative distance 0 cm) recovered a mean thumb-index opening of 9.1 (SEM 1.7) cm. Of the 6 patients who had an opening of 6.3 (SD 1.6) cm before surgery, this distance increased by 2.9 (SEM 0.8) cm. After reconstruction, the average active palmar abduction of the thumb was 45° (SEM 2°) (range 30–60°).

4.4. Project to implement a tetraplegia upper extremity surgery service in Hungary from 2002 to 2016

Despite initial difficulties we could start a teraplegia upper limb surgery service at the Orthopedic Department of Jósa András County Hospital, Nyíregyháza in 2002. The rehabilitation background was provided by the local rehabilitation department and the National Medical Rehabilitation Institute.

The reconstructive upper limb surgery became a recognized part of the treatment protocol in tetraplegia and in rehabilitation medicine. Today all tetraplegic patients in Hungary have the possibility for upper limb reconstruction surgery.

Overall, 141 tetraplegic patients were examined. Of these, 57 patients (10 females, 47 males) were treated with 126 surgical reconstructions, including 366 procedures, on 80 upper extremities (i.e. 23 bilaterally) between 2002 and 2012. Both objective measurements and patient-reported outcomes according to House demonstrated substantial functional gains after surgery. The majority of patients reported improvements in important daily activities after surgery. No patient was worse after surgery. Seventy-four percent of patients reported improvements in 1 or several of the following items: washing, brushing teeth, using utensils, dressing upper extremity, writing, wheelchair propulsion, handling small objects and opening doors. No or limited changes were reported for:

dressing lower extremity, transfer to and from the car, couch, toilet and bed, and several activities that required either good shoulder muscle strength or fine motor control.

Between 2009 and 2017 six international courses on “Tendon Transfer in Tetraplegia” were organized in Hungary with overall 180 participants from 28 countries. In 2014 I had an invitation to visit the Hand Trauma Center, Trzebnica, Poland to help by launching a new tetraplegia hand surgery service. Six reconstructive upper limb surgeries were performed. Tetraplegia upper limb surgery in Poland has been started.

4.5. Complications

126 upper limb reconstructions were performed in 57 patients between 2002 and 2012. In 50 cases triceps and 76 cases of grasp and key-pinch reconstruction were performed. The complication rate was less than 4%, and included haematoma (n = 2), wound infection, granuloma (n = 2) and elbow extension deficit of 30° (n = 1). The haematoma was evacuated, the granuloma was removed and complete wound healing was achieved. The loss of elbow flexion strength was caused by the tendon-muscle-tendon unit overstretching, but after a Z-tenotomy distally full elbow flexion and range of motion was obtained.

5. Conclusions

Based on our results the following conlusions can be derived:

5.1. Modified surgical technique for restoration of lost elbow extension

1. The aponeurosis size of the posterior deltoid (PD) muscle allows **to enlarge the overlap between the posterior deltoid and the proximal donor graft from 45 mm to 70 mm.**

2. The distal end of the graft can be secured a **mechanically firmer insertion into the triceps tendon and into the bone tunnel of the olecranon.**

3. **Early postoperative active shoulder and wrist training** can be started. From the 4th week active elbow exercises are allowed against resistance in horizontal plane in limited range of motion.

5.2. The Alphabet procedure

1. Due to the strong side-to-side double running suture technique, **the traditional two-stage grasp and key-pinch and release operation can be performed in one-stage**, reducing the two stage operations - two rehabilitation periods into one.

2. **Early postoperative mobilization** can reduce the risk of adhesions and hand edema from developing can be avoided, donor muscle strength can be preserved.

5.3. Restoration of active abduction of the thumb

1. In tetraplegic patients who have the muscle strength of extensor digiti minimi at least 3 MRC, the **arthrodesis of the I. CMC joint can be replaced by extensor digiti minimi to abductor pollicis brevis (EDM-APB) tendon transfer**.

2. After EDM-APB tendon transfer the **thumb control can be improved by key-pinch, active thumb-index opening can be increased.**

5.4. Project to implement a tetraplegia upper extremity surgery service in Hungary from 2002 to 2016

1. Although numerous case series have demonstrated that elbow extension and handgrip can be restored reliably in tetraplegic patients, the quality of their life and hand function can be improved, in many countries tetraplegia upper extremity surgery is rarely performed. Multiple barriers can hinder of upper limb reconstruction, including scepticism within patient and non-surgical communities towards surgical rehabilitation, shortage of hand surgeon with sufficient experience, lack of information about these procedures, weak interdisciplinary relationship and insufficient support for tetraplegic patients.

2. **The hand surgeon must take a leadership role** in removing obstacles: to gain the rehabilitation experts' trust and support.

Another option is to directly approach patients and to offer assessment and inform them about surgery and in selected cases carry out successful operations, create a website for patients, present the results at conferences, arrange lectures for doctors interested in tetraplegia rehabilitation, publish scientific articles in the field of tetraplegia hand surgery and rehabilitation and invite media, to gain the support of city and hospital authorities, creating an infrastructure.

3. **Tetraplegia upper limb surgery courses** can popularize the upper limb surgeries in tetraplegic patients.

4. The **rehabilitation protocol of tetraplegic patient** should include the upper limb reconstructive surgery

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