Current Procedure of Double Free Muscle Transfer for Traumatic Total Brachial Plexus Palsy

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Introduction

We describe the current procedure of not only double free muscle transfer but also supplemental techniques including nerve transfer for shoulder and elbow reconstruction and secondary surgery for the wrist and fingers to improve prehensile function following traumatic total brachial plexus palsy¹⁻⁴.

Since 1982, we have performed 362 free innervated muscle transfers for extremity reconstruction, and 305 of these procedures were done to treat brachial plexus palsy. Sixty-five of the 305 patients underwent the current operative protocol of double free muscle transfer, and the functional outcome of thirty-six patients along with the results of a quality-of-life evaluation was reported in our original article⁵. Different surgeons have reported modifications of the double free muscle transfer technique. However, their results have been unsatisfactory. This may be due, in part, to suboptimal postoperative rehabilitation^{6,7} and the fact that additional reconstructions did not accompany the muscle transfer. The key factors in the success of double free muscle transfer include not only meticulous microsurgical technique but also aggressive and sustained rehabilitation, which usually lasts for one and a half years^{3,4}. This requires trained rehabilitation therapists and sound financial support.

Subtle changes in the original double free muscle transfer procedure have led to improved functional outcomes. Stability of the proximal joints is a primary requisite for hand function. Stability of the shoulder and elbow joints is necessary for proper transmission of the power of the transferred muscle to achieve effective hand function in double free muscle transfer. Hence, we attempt to restore shoulder function by nerve transfers⁸. Not only movement of the elbow but also its stability is extremely important for optimal use of the hand⁹. Early passive mobilization of the grafted muscle is also imperative to prevent adhesions and promote smooth gliding¹⁰. The focus of prehensile reconstruction in patients with brachial plexus palsy has

thus shifted from the previous simple nerve-crossing procedures to the use of free innervated muscle transfer with multiple nerve crossings. Free innervated muscle transfer not only imparts motion but also provides stability to multiple joints simultaneously.

The traditional method of monitoring the flap viability with use of a skin paddle is not reliable enough to allow salvage of the muscle graft from vascular compromise. Hence, we recommended measuring compound muscle action potentials (CMAPs) for postoperative flap monitoring¹¹⁻¹³.

Our recent studies on functional outcomes and quality-of-life recovery⁵ have further confirmed the importance of stability and function of the shoulder and elbow to achieve better hand function.

The current procedure of double free muscle transfer consists of the following major steps:

Step 1: Preoperative Planning

Coronal and transverse MRIs and intraoperative electrical stimulation are useful for nerve-root evaluation.

- Even in the setting of a total palsy, fewer than 20% of patients demonstrate avulsions of all five roots of the brachial plexus³. In particular, the C5 nerve root is usually spared from avulsion. This nerve root plays a key role in shoulder reconstruction and has a substantial impact on the functional outcome of the double free muscle transfer technique.
- There are many methods of evaluating the level of nerve root injury. These include preoperative clinical examination¹⁴; electrophysiological studies; radiographic studies; intraoperative macroscopic and microscopic evaluations; intraoperative electrical stimulation; histopathological studies; and measurement of somatosensory evoked potentials, evoked spinal cord potentials, and choline acetyltransferase activity¹⁵. Among the radiographic studies, coronal and transverse

magnetic resonance images (MRIs)¹⁶ (Fig. 1) are a simple and reliable indicator. Measurements of evoked spinal cord potentials and choline acetyltransferase activity were found to be the most reliable methods of evaluating the possibility of nerve root repairs¹⁵, but both these techniques are not universally available. We recommend using intraoperative electrical stimulation (Nerve Stimulator; Keisei Medical Industrial, Niigata, Japan) to assess the reparability of cervical roots.

- Appropriate timing and a suitable combination of the surgical procedures are very important and are guided by several criteria. Earlier, we performed Stage I and Stage II together as the first procedure. More recently, we have performed these procedures separately due to the prolonged duration of the combined surgery. Thus, Stage I consists of nerve transfer for shoulder reconstruction. Stage II consists of free innervated muscle transfer to restore elbow flexion and finger extension. We perform Steps 4 and 5 together (Stage III), usually two or three months after the first free muscle transfer. This stage involves both the free muscle transfer along with motor nerve repair for elbow extension. Hence, in patients presenting later than six months after injury, we perform this stage earlier than Stage II/Step 3. We perform secondary procedures (Step 7) approximately 1.5 years after the first stage of the operation, depending on the degree of recovery.

Step 2: Reconstruction of Shoulder Function (Stage I)

If the nerve gap is <10 cm, use the sural nerve as an interpositional graft; if the nerve gap is >15 cm, use a vascularized ulnar or radial nerve graft from the ipsilateral forearm; if the ipsilateral nerve roots are not available, explore the contralateral plexus.

- Explore the upper roots through a transverse cervical incision for supraclavicular injury. To explore the lower roots and plexus, use a transverse incision just above the clavicle to minimize postoperative scarring. Identify the C5 and C6 nerve roots in the interval between the palpable posterior tubercle of the C5 transverse process and anterior tubercle of the C6 transverse process. Once the nerve roots are identified, trace them distally to locate the level of the lesion. Perform electrical stimulation of these roots. If the proximal muscles such as the rhomboids or serratus anterior contract, the lesion is postganglionic and the nerve root is repairable. If more distal muscles such as the supraspinatus or

deltoid contract, the lesion is infraclavicular. If no muscular contraction occurs, the lesion may be preganglionic or intraforaminal and is not repairable.

- Next, explore the lower three cervical roots (C7, C8, and T1) and the upper trunk of the brachial plexus through the transverse supraclavicular skin incision. Preserve the transverse cervical vessels carefully, as they can be used as recipient vessels if a free vascularized ulnar nerve graft is required. Dissect further into the supraclavicular fossa and identify the suprascapular nerve and posterior division of the upper trunk. If the nerve gap is <10 cm, use the sural nerve as an interpositional graft between the C5 root and the suprascapular nerve and posterior division of the upper trunk. If the nerve gap is long (>15 cm) or the diameter of the required graft is large, use a vascularized ulnar or radial nerve graft from the ipsilateral forearm (Fig. 2-A).
- If the ipsilateral nerve roots are not available, explore the contralateral plexus. Identify the anterior and posterior divisions of the contralateral C7 root by nerve stimulation. Divide the C7 root and prepare it for transfer (Fig. 2-B)
- Connect the proximal end of the harvested ulnar nerve graft to the contralateral C7 root using an epiperineurial suture technique. (When we connect a large nerve with many fascicles such as the ulnar nerve and nerve root, we use the epiperineurial suture technique. When we connect a small nerve with few fascicles [fewer than three], we prefer to use the funicular technique [see Step 3].) Then anastomose the vascular pedicle of the free vascularized ulnar nerve graft (the superior ulnar collateral artery and vein) to the contralateral transverse cervical artery and vein. Pass the distal end of the ulnar nerve through a subcutaneous tunnel in the upper chest region and connect it to the target nerve, such as the suprascapular nerve or the posterior cord in the supraclavicular or infraclavicular region.

Step 3: First Free Innervated Muscle Transfer for Elbow Flexion and Finger Extension (Stage II)

Prepare the recipient site, harvest the gracilis muscle, and transfer the muscle graft.

Preparation of the Recipient Site

- Through a transverse lateral supraclavicular incision, explore the spinal accessory nerve after detaching the trapezius insertion from the clavicle and acromion. Take care not to injure the previously transferred nerves in the medial

supraclavicular fossa. Divide the distal branch of the spinal accessory nerve and transfer it to the supraclavicular fossa. Extend the incision along the deltopectoral crease and explore the thoracoacromial artery and cephalic vein.

- Make a curvilinear incision over the anterior cubital fossa. Dissect underneath the brachioradialis and long wrist extensor muscles to create a pulley for the transferred muscle. Now, make a subcutaneous tunnel between the deltopectoral incision and the cubital incision.
- Make another curvilinear incision over the dorsal aspect of the forearm. Dissect and prepare the extensor digitorum communis tendons to receive the tendon of the transferred muscle.

Harvesting the Gracilis Muscle

- Use a small transverse incision over the medial aspect of the upper part of the thigh to dissect the gracilis muscle. This avoids a long and cosmetically unacceptable scar at the donor site. Complete the dissection of the distal tendinous portion of the muscle through two small incisions over the distal part of the thigh and the antero-medial aspect of the upper part of the leg.
- Harvest the entire gracilis muscle from its origin at the pubis to its insertion over the tibia. Use the contralateral gracilis for this stage because of the favorable position of the vascular pedicle with respect to the recipient vessels (Fig. 3-A).
- Measure the length of the gracilis muscle under maximal traction before detaching the pubic origin. This helps in adjusting the correct tension of the muscle at the time of final suturing (Fig. 3-B).

Transfer of the Muscle Graft

- Suture the tendon of origin of the gracilis to the acromion and lateral clavicle with the help of drill-holes, placing it superficial to the anterior portion of the deltoid muscle. Pass the muscle and its distal tendon through the subcutaneous tunnel in the anterior aspect of the arm. Now, pass it underneath the pulley created by the brachioradialis and radial wrist extensor muscles. This pulley should be close to the elbow, to prevent bowstringing of the transferred muscle.
- Pass a Penrose drain (7-mm diameter) under the clavicle to the supraclavicular fossa. Secure the distal end of the motor nerve of the gracilis muscle to the drain using a 4-0 nylon suture. Gently pull out the drain proximally to bring the motor nerve into the subclavicular fossa.
- Perform the coaptation of the distal branch of the spinal accessory nerve to the motor branch of the gracilis with the funicular suture technique under an operating microscope (Fig. 3-C and

Video 1).

- Anastomose the nutrient vessels of the muscle to the thoracoacromial artery and cephalic vein.
- Weave the distal tendon twice through the extensor digitorum communis tendons. Pull the tendon distally to restore its original length. Perform the tension adjustment with the shoulder in 30° of flexion, the elbow in 90° of flexion, the wrist in neutral, and the fingers in complete extension (Video 2).
- Secure the distal tendon juncture with multiple nonabsorbable sutures.

Steps 4 and 5 (Stage III): Nerve Transfer for Elbow Extension and Sensory Restoration (Step 4) and Second Free Innervated Muscle Transfer for Elbow Flexion and Finger Flexion (Step 5)

Repair the long-head branches of the triceps brachii muscle of the radial nerve by using the third and fourth intercostal nerves, and the median nerve by using the sensory branch of the second and third intercostal nerves; then transfer the second free muscle.

Nerve Transfers

- Begin the dissection with a linear incision over the medial aspect of the upper arm, extending it in a curvilinear fashion along the midaxillary line with a transverse portion along the sixth rib up to the costochondral junction. Identify and protect the intercostobrachial nerve, a branch of the second intercostal nerve. Secure the long thoracic nerve running down posteriorly along the midaxillary line. Incise the anterior surface of the second to sixth ribs along the center of its width. Take care not to injure the serratus anterior muscle. Elevate the anterior and posterior periosteum, taking due care of the pleura. Dissect each intercostal nerve without an osteotomy of the ribs and mobilize the nerves to reach the axilla.
- Dissect the median nerve and motor branch to the triceps muscle at the level of the axilla. Divide these nerves and transfer them downward for a tension-free neurorrhaphy with the intercostal nerves.
- Make an incision on the anteromedial aspect of the cubital fossa. Dissect underneath the pronator teres and long wrist flexor muscles to create a pulley.
- Make a subcutaneous tunnel along the medial aspect of the arm to connect the two incisions.
- Through a curvilinear incision over the anterior aspect of the forearm, dissect and prepare the

flexor digitorum profundus tendons.

- Complete the nerve transfer of the intercostobrachial nerve and sensory branch of the second and third intercostal nerves to the median nerve for restoration of hand sensory function. Then, transfer the third and fourth intercostal nerves to the long-head branches of the triceps muscle of the radial nerve to restore activation of the elbow extensors (Fig. 4 and Video 3).

Free Innervated Muscle Transfer

- Harvest the entire gracilis muscle from the ipsilateral thigh in the same manner as described in Step 3. Make four drill-holes in the second and third ribs to attach the origin of the muscle graft using Ethibond sutures. Pass the muscle through the subcutaneous tunnel along the medial aspect of the arm. Then pass the distal tendon under the pulley created by the pronator teres and long wrist flexors, just distal to the elbow.
- Anastomose the nutrient vessels to the thoracodorsal artery and vein. Complete the nerve connection between the fifth and sixth intercostal nerves to the motor nerve of the gracilis.
- Weave the distal tendon through the flexor digitorum profundus tendon (Fig. 5). Adjust the muscle tension according to the principles described in Step 3. Complete the suturing of the distal tendon juncture in a similar position; expect that the fingers are kept in flexion.

Step 6: Postoperative Management

Immobilize the upper limb for eight weeks, and start early passive mobilization at one week.

After each muscle transfer, immobilize the upper limb with the use of an arm brace and cast with the shoulder in 30° of abduction and flexion and 60° of internal rotation, the elbow in 100° of flexion, the wrist in the neutral position, and the fingers in forced flexion or extension for eight weeks. Subsequently, a sling is used to prevent subluxation of the glenohumeral joint until recovery of the shoulder girdle muscles.

- Start early passive mobilization one week after the free muscle transfer. We have reported the details of our rehabilitation program in our previous articles¹⁰ (Figs. 6-A and 6-B).

Step 7: Secondary Procedures (Stage IV)

Secondary procedures include wrist fusion, correction of intrinsic minus deformity, etc.

Wrist Fusion

- If the wrist remains unstable in spite of prolonged splinting, fuse the wrist joint in the neutral position or mild dorsiflexion using a dynamic compression plate. This helps improve control and transmits greater motor power to the fingers^{17,18} (Fig. 7-A).

Correction of Intrinsic Minus Deformity

- A claw finger deformity frequently develops after satisfactory recovery of finger flexion and extension. This can be prevented to some extent by the use of a static volar splint; however, most patients need secondary corrective procedures. We use Zancolli's metacarpophalangeal joint capsulodesis¹⁹ (Fig. 7-B) or transient interphalangeal joint fixation with Kirschner wires for claw correction. The choice of the procedure depends on the patient's performance during the preoperative trial with a simulation splint⁴.

Results

From 2002 to 2008, thirty-six patients underwent reconstruction with the double free muscle technique to treat a total brachial plexus palsy⁵. There were three female and thirty-three male patients. The dominant and nondominant sides were affected in eighteen patients each. The mean time from injury to the first stage of the reconstruction was four months (range, one to seventeen months), with the exception of three patients who presented to us very late (more than 100 months after the injury). The average duration of follow-up after the second free innervated muscle transfer was thirty-six months (range, twenty-four to seventy-nine months). All patients were followed for a minimum of twenty-four months after the second free innervated muscle transfer. The data pertaining to the patient details and overall functional results at the last follow-up are summarized in the original article⁵.

The power of elbow flexion was M4 in twenty-five patients and M3 in eleven patients according to the modified Highet scale²⁰. Quantitative isokinetic measurements of elbow flexion, performed in twenty-one patients, revealed that the reconstructed limb had regained a concentric elbow flexion of 5 N-m (13% of that of the contralateral, normal limb) and eccentric elbow flexion of 8 N-m (15% of that of the contralateral, normal limb). The total active motion of the fingers was excellent ($\geq 60^\circ$) in eleven patients, good (30° to 55°) in seventeen patients, fair (5° to 25°) in seven patients, and poor (0°) in one patient.

Illustrated Case

A nineteen-year-old man underwent the entire double free muscle transfer procedure. Stage I included nerve

transfer of the C5 root to the suprascapular nerve and the posterior division of the upper trunk. Stages II and III consisted of the two gracilis free muscle transfers and the nerve transfers for elbow extension and sensory restoration. Stage IV consisted of secondary procedures—i.e., wrist fusion and Zancolli capsulodesis for claw correction.

At a recent follow-up visit, thirty-six months after Stage IV, the patient had shoulder abduction of 40°, flexion of 40°, and external rotation of –10°. Elbow flexion was 140°, with a motor grade of M4. The elbow joint was stable with good control and active extension. He had good active finger flexion and extension with a total active range of motion of 90°. He could achieve a grip strength of 17 kg as measured with a digital hanging scale (Kansai Scale, Osaka, Japan). The Disabilities of the Arm, Shoulder and Hand (DASH) score improved by 24 points, from a preoperative score of 58 points to a postoperative score of 34 points (Figs. 8-A through and 8-E and Video 4).

What to Watch For

Indications

- Total paralysis of the brachial plexus
- Acute cases (less than six months after injury)
- Failed or chronic cases (more than seven months after injury), with available donor motor nerves (spinal accessory and intercostal nerves)
- Age of less than fifty years
- Patient's motivation and financial ability to sustain and continue postoperative rehabilitation for more than one year

Contraindications

- Age of more than sixty years
- Accompanying major systemic injury such as head or spinal cord injury
- Associated vascular trauma (e.g., subclavian artery injury) with no suitable recipient vessels

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Pitfalls & Challenges

- The transferred muscle can undergo ischemic necrosis without ischemic changes in the monitoring skin paddle. Postoperative monitoring of compound muscle action potentials can avoid this major complication.
- Poor recovery of motor power of the grafted muscle, especially the second muscle graft

Clinical Comments

- Are patients for whom conventional transfer of intercostal nerves to the musculocutaneous nerve has failed still candidates for double free muscle transfer?

No. Unless the lower intercostal nerves (such as the sixth and seventh) are available as donor motor nerves for the second muscle graft, double free muscle transfer cannot be performed in these patients. In suitable candidates undergoing double free muscle transfer, adequate precautions and care should be taken to avoid damage to the previously transferred intercostal nerves. Electrical stimulation should be used judiciously during dissection.

- Can patients in whom the spinal accessory nerve has been used for transfer to the suprascapular nerve be candidates for double free muscle transfer?

Yes. The phrenic nerve can be used as the donor motor nerve of the first muscle graft in such cases.

- How do you treat the unstable/flail shoulder in chronic cases or those with poor motor recovery after failed nerve transfers?

We recommend a glenohumeral joint fusion in most of such cases. The upper trapezius and serratus anterior muscles provide mobility and stability to the scapula.

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Figures

Fig. 1-A

Figs. 1-A and 1-B MRIs of a patient with brachial plexus palsy. Fig. 1-A Coronal view showing no visible anterior nerve roots on the right side. C5 = C5 nerve root.

Fig. 1-B

Transverse view of the C5 nerve root showing no anterior rootlet on the right side (arrow).

Fig. 2-A

Free vascularized nerve graft (FVNG) between the C5 nerve root and the suprascapular nerve (SSN) and upper trunk following anastomoses of the nutrient vessels to the transverse cervical artery and vein (a.v.).

Fig. 2-B

Vascularized ulnar nerve graft (VUNG) between the contralateral C7 nerve root and the suprascapular nerve (SSN), posterior cord (PC), and long thoracic nerve (LT) following anastomoses of the nutrient vessels (a.v.) to the transverse cervical artery and vein.

Fig. 3-A

Marking of the skin incision on the contralateral thigh for harvesting of the gracilis muscle graft.

Fig. 3-B

The harvested gracilis muscle. The original length was restored by the surgeon pulling both ends of the graft.

Fig. 3-C

Stage II of the procedure, in which the first gracilis muscle graft is used to restore elbow flexion and finger extension. EDC = extensor digitorum communis. (Reproduced, with modification, from: Doi K. Basic knowledge of current diagnosis and treatment of brachial plexus paralysis for inexperienced orthopedic surgeons [in Japanese]. J Jpn Orthop Assoc. 2009;83:377-89.)

Fig. 4

Stage III of the procedure: sensory restoration of the hand with nerve transfer of the intercostobrachial nerve and sensory rami of the second and third intercostal nerves to the median nerve and reconstruction of elbow extension with nerve transfer of the third and fourth intercostal nerves to the long-head branches of the triceps brachii muscle of the radial nerve (RN). ICN = intercostal nerve.

Fig. 5

Stage III of the procedure, in which the second gracilis muscle graft is used to restore elbow flexion and finger flexion. FDP = flexor digitorum profundus; ICN 5, 6 = the fifth and sixth intercostal nerves (Reproduced, with modification, from: Doi K. Basic knowledge of current diagnosis and treatment of brachial plexus paralysis for inexperienced orthopedic surgeons [in Japanese]. J Jpn Orthop Assoc. 2009;83:377-89.)

Fig. 6-A

Early passive mobilization of the muscle-tendon graft by manual movement of the finger and wrist joints.

Fig. 6-B

Early passive mobilization of the muscle-tendon graft by manual movement of the finger and wrist joints.

Fig. 7-A

Wrist fusion with a dynamic compression plate and screws.

Fig. 7-B

Capsulodesis of the metacarpophalangeal joint for static correction of claw finger deformity, by proximal advancement of the distally based flap of the volar plate. The volar plate is anchored to the metacarpal neck (see the long finger).

Fig. 8-A

Figs. 8-A through 8-E Illustrative case. Functional outcome three years after the double free muscle transfer procedure. Fig. 8-A Shoulder abduction.

Fig. 8-B

Elbow flexion.

Fig. 8-C

Elbow extension.

Fig. 8-D

Finger flexion.

Fig. 8-E

Finger extension.

Fig. 1-A

Fig. 1-B

Fig. 2-A

Fig. 2-B

Fig. 3-A

Fig. 3-B

Fig. 3-C

Fig. 4

Fig. 5

Fig. 6-A

Fig. 6-B

Fig. 7-A

Fig. 7-B

Fig. 8-A

Fig. 8-B

Fig. 8-C

Fig. 8-D

Fig. 8-E