14 Functional Reconstruction of the Upper Extremity

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With the development of microsurgery, microneurovascular muscle transfer and transplantation are gradually used to restore active functions of extremity damaged following traumatic muscle loss of the upper extremity or peripheral nerve injury, especially brachial plexus injury. This is microsurgical reconstruction of limb function.

Free functioning muscle transplantation (FFMT) is a procedure that involves microneurovascular transfer of a muscle to reconstruct the function of upper extremity following traumatic muscle loss and brachial plexus injury. Viability of the transferred muscle is maintained by microvascular anastomosis between the muscle's artery and vein and a suitable artery and vein in the recipient area. Reinnervation and active muscle contraction are achieved by suturing a motor nerve in the recipient area to the motor nerve of the transferred muscle. However, besides the cost of sacrificing the function of the donor muscle, two other problems also need to be considered regarding survival and reinnervation of the transferred muscle. Therefore, FFMT still has problems to be resolved, like donor site morbidity and possibility of failure. To improve the reconstructed function of the upper extremity, it is very important to conduct related clinical research to establish technical norms and standards of FFMT.

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14.1 Functional Reconstruction for Traumatic Muscle Loss of the Upper Extremity

14.1.1 Bipolar Transfer of Pedicled Sternocostal Part of Pectoralis Major Muscle for Elbow Flexion

1. Indications

   Severe crush injury involving the upper extremity from the arm to the elbow, or elbow flexion muscle loss (biceps, brachialis and brachioradialis) due to necrosis and infection, with nearly normal muscle strength of the sternocostal part of pectoralis major muscle (M 4–5).
2. Surgical methods
   (a) Surgical design. (1) Donor muscle: sternocostal part of pectoralis major muscle; (2) Neurovascular pedicle: thoracoacromial artery and vein, medial pectoral nerve (branched from medial cord, C8 and T1); (3) Design of the pedicled sternocostal part of pectoralis major muscle flap: the size of the flap is approximately 12–15 cm × 3–5 cm based on the skin defect of the arm after muscle transfer.
   (b) Anesthesia and position. The procedure is performed with the patient under general anesthesia and in a supine position (Fig. 14.1a).
   (c) Harvest of the sternocostal part of pectoralis major muscle. (1) A long incision is made from the coracoid process to the insertion of the pectoralis major muscle, along its lateral aspect, continuing to the level of the axilla with the forearm held in a neutral position; (2) The entire mass of the pectoralis major muscle is then detached from its origin along the medial half of the clavicle and its sternocostal border. While the

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Fig. 14.1 A patient with hemophilia and necrosis of medial flexors of the arm due to infection (**a**). Bipolar transfer of pedicled sternocostal part of pectoralis major muscle was performed to cover the wound and reconstruct elbow flexion (**b**-**e**). Survival of the muscle flap (**f**). Postoperative rehabilitation (**g**)

pectoralis major is elevated from the chest wall and the underlying pectoralis minor, meticulous care must be given to preservation of its neurovascular pedicles (Fig. 14.1b–e).

(d) Bipolar transfer of the sternocostal part of pectoralis major muscle. (1) Placement of the sternocostal part of pectoralis major muscle: a second S-shape incision is made over the antecubital fossa to expose biceps tendon with shoulder adduction and elbow extension. The origins of the sternocostal heads with attached anterior rectus abdominis sheath are rolled into a tube which is directed downwards the arm through an anterior subcutaneous tunnel, exiting through the second incision; (2) Fixation of the insertion: the humeral attachment of the muscle is directed cephalad and sutured securely to the coracoid process with suture anchors (Schottstaedt's procedure, by contrast with Carroll-Kleinman's procedure in which the attachment of the muscle is sutured to the acromion). The origins of the sternocostal heads are sutured to the biceps tendon using a Pulvertaft weave and nonabsorbable sutures with the muscle under appropriate tension and the elbow flexed to 45°; (3) The incision is closed in layers (Fig. 14.1d, e).

3. Critical points
   (a) Bipolar transfer of pedicled sternocostal part of pectoralis major muscle is more suitable for male patients than for female ones due to its adverse effect on the appearance of the breast.
   (b) Care should be taken not to stretch the neurovascular pedicle when the sternocostal part of pectoralis major muscle is harvested.
   (c) Postoperative protocol. Immediately after the surgery, the shoulder is immobilized in 60° of flexion and 30° of abduction and with the elbow in 90° of flexion. At the end of the second week, rehabilitation is started under protection, but passive or active extension of the elbow more than 60° is prohibited until the seventh postoperative week when the splint is removed (Fig. 14.1f).

14.2 Functional Reconstruction for Traumatic Muscle Loss of the Upper Extremity

14.2.1 Microneurovascular Transfer of Gracilis Muscle for Finger Flexion

1. Indications

   Severe injury of upper extremity from elbow to forearm, resulting in the defect of forearm flexors.

2. Surgical methods
   (a) Surgical design. (1) Donor muscle: gracilis muscle. (2) Recipient nerve: anterior interosseal nerve or brachialis muscle branch of musculocutaneous nerve. (3) Recipient vessels: brachial artery and brachial or cephalic vein.
   (b) Harvest of the donor muscle. Critical points: A line is drawn from the pubic tubercle along the adductor longus prominence to demarcate the anterior border of the gracilis. A flap is designed which is 6–10 cm distal to the pubic tubercle, with a size of about 5 × 15–18 cm (Fig. 14.2). We incise the anterior border of skin paddle firstly. The vascular pedicle and motor branch of the obturator nerve of the gracilis are confirmed through the intermuscular septum between the gracilis and the adductor longus, commonly located 8–12 cm inferior to the pubic tubercle (Fig. 14.3). The adductor longus is mobilized posteromedially and the pedicle is dissected from its origin of the profunda femoris vessels, with the longest possible pedicle (6–8 cm). The gracilis motor nerve should be followed as proximally as possible to the obturator foramen, with a length of 8–12 cm. Then,

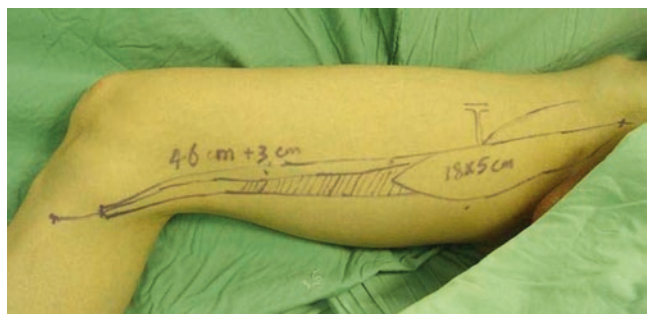

Fig. 14.2 Surgical design of gracilis muscle flap

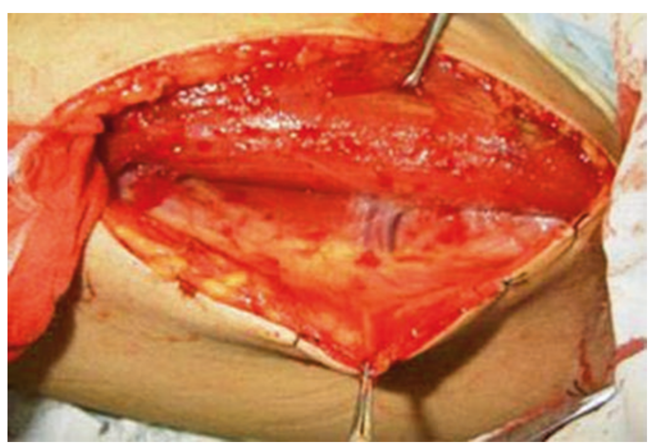

Fig. 14.3 Exposure of vascular pedicels of the gracilis muscle flap

we continue to dissect the belly and tendon of the gracilis, including the fascia around the gracilis. Finally, the vascular pedicle and nerve of the gracilis are ligated and cut respectively, and dissection of the gracilis is completed proximally up to its origin from the pubic arch (Fig. 14.4).

(c) Microneurovascular transfer of gracilis muscle for finger flexion. The gracilis muscle flap is placed above the arm, elbow and forearm, with the proximal site of muscle anchored to the medial brachial intermuscular septum. The distal tendon is then woven into the flexor digitorum profundus and flexor pollicis longus tendons using a Pulvertaft weave. The vascular anastomosis is performed under a microscope, with the artery and vein of the gracilis anastomosed to the brachial artery (end to side) and cephalic vein (or brachial vein), respectively. The gracilis motor nerve is sutured with anterior interosseal nerve or brachialis muscle branch of musculocutaneous nerve (Fig. 14.5).

3. Critical points
   (a) The entire gracilis muscle and its tendon should be harvested to maximize the length. The pedicle is dissected from its origin in the profunda femoris vessels, with the longest possible pedicle. The gracilis motor nerve should also be followed as proximally as possible to the obturator foramen.
   (b) The nerve bundle to the gracilis should be evaluated and trimmed to confirm that there are more than two motor branches.
   (c) The gracilis motor nerve should be confirmed by electrical stimulator to identify its relationship with muscle fibers. If necessary, the muscle could be divided into two separate motor units based on the direction of the muscle fibers.
   (d) The length of the motor branch should be reduced as much as possible in conditions of suitable muscle tension to reduce the time needed for nerve regeneration.
   (e) Postoperatively the upper limb is immobilized for 4–6 weeks with the elbow in 30° of flexion, the forearm in supination and the hand in functional position.
   (f) Rehabilitative treatment plays an active role in nerve regeneration, and regular follow-up to evaluate the muscle function is also very important to obtain good functional outcomes.

Fig. 14.4 Gracilis muscle flap

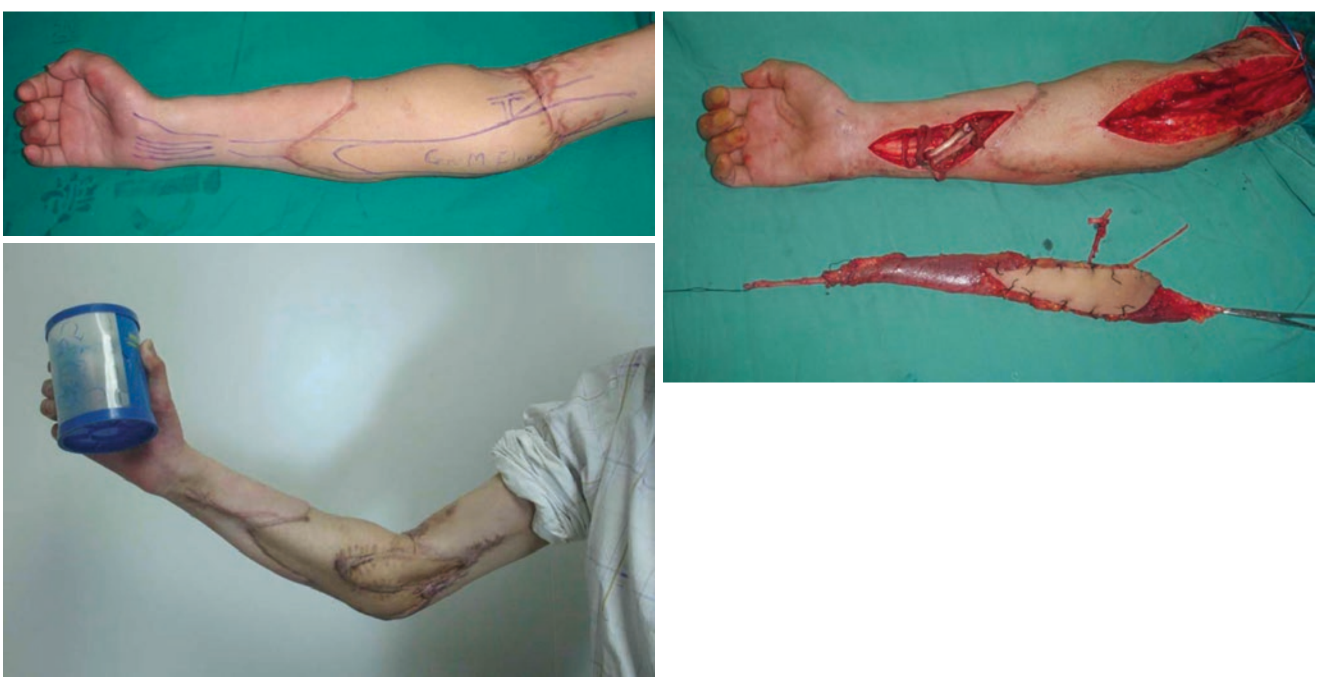

Fig. 14.5 Microneurovascular transfer of gracilis muscle for finger flexion following severe injury of upper extremity

To address the usage of brachialis muscle branch of musculocutaneous nerve (BMBMCN) as a recipient nerve, a microanatomical study of 30 limbs from 15 adult cadavers performed by Zhou and Gu [1] shows that there are three branching types observed: type I, single branch in 25 limbs (83.33%); type II, two branches in 1 limb (3.33%); and type III, multiple branches in 4 limbs (13.33%). The mean length of BMBMCN is 52.66 ± 6.45 mm, and its mean diameters 1.39 ± 0.10 mm. The average number of nerve fibers of brachialis muscle branch of musculocutaneous nerve is 2.83 ± 0.46, and that of myelinated nerve fibers 1964.71 ± 310.32.

14.3 Functional Reconstruction for Traumatic Muscle Loss of the Upper Extremity

14.3.1 Microneurovascular Transfer of Gracilis Muscle for Wrist and Finger Extension

1. Indications

   Severe injury of upper extremity from elbow to forearm, resulting in the defect of forearm extensors and partial injury to the flexors of the hand and wrist (M 0–3).
2. Surgical methods
   (a) Surgical design. (1) Donor muscle: gracilis muscle. (2) Recipient nerve: posterior interosseal nerve or brachialis muscle branch of musculocutaneous nerve. (3) Recipient vessels: brachial artery and brachial or cephalic vein.
   (b) Harvest of the donor muscle, as described previously.
   (c) Microneurovascular transfer of gracilis muscle for wrist and finger extension. The gracilis muscle flap is placed at the dorsal side of the arm, elbow and forearm, with the proximal site of muscle anchored to the lateral brachial intermuscular septum. The distal tendon is then woven into the extensor digitorum communis and extensor pollicis longus tendons using a Pulvertaft weave. The vascular anastomosis is performed under a microscope, with the artery and vein of the gracilis anastomosed to brachial artery (end to side) and cephalic vein (or brachial vein), respectively. The gracilis motor nerve is sutured with posterior interosseal nerve or brachialis muscle branch of musculocutaneous nerve.
3. Critical points

   Postoperatively the upper limb is immobilized for 4–6 weeks with the elbow in 30° of flexion, the forearm in pronation, and the wrist and hand in functional position.

14.3.1.1 A Case Report

Wu Yongxian, male, 26 years old, complained of limited mobility of the left hand due to a gunshot injury for 11 months. The main problem was defective extensors of the left elbow and forearm, in addition to complete injury of left radial nerve and partial injury of the left ulna and median nerves. On June 6, 2012, a functional gracilis muscle transfer was performed to reconstruct his finger extension. The recipient vessels and nerve were brachial artery and vein and brachialis muscle branch of musculocutaneous nerve, respectively. Six months postoperatively, the transplanted gracilis could contract and functional recovery of wrist and hand extension was achieved to some extent (Fig. 14.6).

14.4 Function Reconstruction for Traumatic Muscle Loss of the Upper Extremity

14.4.1 Microneurovascular Gracilis Muscle Transfer for Elbow Flexion and Finger Extension

1. Indications

   Severe crush injury to the upper extremity involving the arm, elbow and forearm, resulting in defects of elbow flexors and forearm extensors.
2. Surgical methods
   (a) Surgical design. (1) Donor muscle: gracilis muscle. (2) Recipient nerve: trapezius muscle branch of accessory nerve or phrenic nerve. (3) Recipient vessels: brachial artery and brachial or cephalic vein, or transverse cervical artery and external jugular vein.
   (b) Harvest of the donor muscle, as described previously.
   (c) Microneurovascular transfer of gracilis muscle for elbow flexion and finger extension. The gracilis muscle flap is placed from the shoulder, arm and elbow to the dorsal side of the forearm, with the proximal site of muscle anchored to the acromion or the periosteum of the lateral clavicula. The lower part of the gracilis and the tendon are directed to the dorsal incision of the forearm through submuscular tunnel of brachioradialis and extensor carpus radialis and subcutaneous tunnel of forearm. The distal tendon is then woven into the extensor digitorum communis and extensor pollicis longus tendons with the elbow in 90° flexion, and the wrist and hand at extension position. The vascular anastomosis is performed under a microscope, with the artery and vein of the gracilis anastomosed to transverse cervical artery and external jugular vein, respectively. The gracilis motor nerve is sutured with trapezius muscle branch of accessory nerve or phrenic nerve. If only reconstruction

Fig. 14.6 Functional gracilis muscle transfer for wrist and finger extension following severe injury of the upper extremity

of elbow flexion is needed (severe crush injury to the extremity from arm to elbow, resulting in defects of elbow flexors and concomitant injury to latissimus dorsi and pectoralis major, M 0–3), the distal tendon is woven into the biceps tendon.

(d) Critical points

Postoperatively the upper limb is immobilized using plaster for 4–6 weeks with the shoulder in 60° of flexion and 30° of adduction, the elbow in 90° of flexion, and the wrist and hand in extension position.

14.4.1.1 A Case Report

A boy, 4 years old, with the main complaint was open fracture at the left upper extremity (Gustilo IIIc + IIIb) due to a car accident. Debridement, external fixation of the left extremity fracture and ALT-flap using flow-through technique were performed to repair soft tissue and vessel defects simultaneously. In the second stage, microneurovascular transplantation of gracilis muscle was performed to restore his elbow flexion and finger extension of the left extremity (Fig. 14.7).

Fig. 14.7 Functional gracilis muscle transplantation was performed to restore elbow flexion and finger extension

Fig. 14. 7 (continued)

14.5 Functional Reconstruction for Volkmann's Ischemic Contracture

Volkmann's ischemic contracture of the forearm can be one of the most devastating complications following elbow trauma and crush injury, fracture and vascular injury of the forearm. It is a dismay consequence of an acute compartment syndrome which is not diagnosed or treated timely. What's more, sustained ischemia can result in irreversible changes to the forearm flexors, leading to necrosis. Then the necrotic muscle is replaced with fibrotic tissue, clinically presenting as severe irreversible deformity and dysfunction of the limb at the late phase.

Now surgery has been the main treatment for Volkmann's ischemic contracture, including neurolysis, tendon lengthening and transfer, and osteotomy (orthopedic treatment). What's more, functional free muscle transfer with vessel and nerve anastomosis is an effective microsurgical technique to reconstruct the forearm flexors after Volkmann's ischemic contracture of the forearm. The suitable muscles for reconstruction surgery include pectoralis major, gracilis, latissimus dorsi. Currently, in most cases, functional free gracilis transfer for Volkmann's ischemic contracture is reported which has achieved substantial improvements in postoperative function of digital flexion so that the patients can complete simple activities alone.

1. Indications

   Fibrosis and functional loss of the forearm flexors resulting from injuries at the late phase.
2. Surgical techniques
   (a) Surgical design. (1) Donor muscle: the gracilis muscle. (2) Donor motor nerve: the anterior interosseous nerve or brachialis muscle branch. (3) Donor vessels: brachial artery, cephalic vein or brachial vein.
   (b) Harvest of donor muscle: as described previously.

Fig. 14.8 The finger flexion was reconstructed by functional free gracilis muscle transplantation for Volkmann's ischemic contracture of the forearm following rupture of the left brachial artery

(c) Microneurovascular transfer of gracilis muscle for finger flexion. The gracilis muscle is placed along the ventral part of the upper limb. Its proximal origin is sutured to the medial muscle interval of arm. Note that the elbow should be extended to maintain proper muscle tension. Its distal tendon is then sutured to the flexor digitorum profundus tendons and flexor pollicis longus muscle tendon in the distal forearm. The artery of the muscle is anastomosed to the brachial artery, and the vein to the cephalic vein or brachial vein. The anterior branch of obturator nerve is sutured to the anterior interosseous nerve or brachialis muscle branch.

3. Critical points

   The elbow is maintained in a position of 30° of flexion, the forearm in supination, and the wrist and hand in functional position. Plaster immobilizes the upper limb for 4–6 weeks.

14.5.1 A Case Report

Functional free gracilis transfer with vessel and nerve anastomosis was performed to reconstruct the digital flexion of a patient on 3rd, December, 2009. Fifteen months later, great improvement was achieved in postoperative digital flexion. The power of finger flexion was from M3 to M4. The patient could grasp light objects (Fig. 14.8).

14.6 Functional Reconstruction for Intrinsic Muscles Injuries

14.6.1 Microneurovascular Transplantation of Extensor Digitorum Brevis Muscle

Shengxiu Zhu et al. (1982) reported reconstruction of thumb opposition and adduction by microneurovascular transfer of the extensor brevis digitorum. A cadaveric study conducted by et al. [2]. involving 30 sides shows that the extensor brevis digitorum is a pennate muscle which has three tendons in 80% of the cases and four tendons in 20% of the cases. The mean length, width and thickness of the extensor brevis digitorum are 6.15 ± 0.40, 3.85 ± 0.04 and 0.21 ± 0.02 cm, respectively. The extensor brevis digitorum is mainly supplied by dorsalis pedis and innervated by branch of nervi peronaeus profundus which can be retrogradely dissected as long as 27.47 ± 2.56 cm. Quantitative analysis shows there are 934.500 ± 57.740 myelinated nerve fibers in the branch of nervi peronaeus profundus.

1. Design of the extensor brevis digitorum flap. Mark the course of dorsal pedal artery, and design the extensor brevis digitorum flap with a size of 6 × 2 cm (for the sake of direct suture of the wound after flap dissection).
2. Exposure of the vessels and nerves. Incision is made at the midline of the ankle anteriorly. Skin, fascia, anterior

talofibular ligament and cruciate ligament are incised. Between the musculi hippicus and the hallucis longus, the vessels and nervi peronaeus profundus are separated. A longitudinal incision, 1–2 cm away from the lateral side of dorsalis pedis, is made to open the periosteum and soft tissue around the tarsometatarsal joint. Then the dorsalis pedis under the tissue is separated. The vessel pedicle supplying the extensor brevis digitorum should be protected.

3. Harvest of the extensor brevis digitorum flap. The flap is harvested from inside to outside, and from distal to proximal along the maker. The margin between the flap and muscle membrane is sutured temporarily. The tendons of the extensor digitorum longus and extensor digitorum brevis of the Second-fourth toes are incised distally to the flap. Then the dissection is performed between the extensor brevis digitorum and the tarsometatarsal joint and the periosteum. The anastomotic vessels around the flap are ligated before the origin of extensor brevis digitorum was incised from the calcaneus anterior to the tarsal sinus. The nervi peronaeus profundus is isolated from the anterior tibial neurovascular bundles through the ankle incision, and its epineurium is incised. Then the branch to the extensor brevis digitorum is isolated, which is confirmed by electrical stimulation.
4. Transfer of the extensor brevis digitorum flap.
   (a) Skin and subcutaneous tissue are incised along the radial side of the palmar crease and thenar stripes, until proximally to the wrist crease. The dissection is performed at both sides of the flap. The scar and abnormal tissue are excised before the extensor brevis digitorum flap transplanted to the hand. To reconstruct the thumb opposition, the proximal part of the extensor brevis digitorum flap is sutured to the distal margin of the transverse carpal ligament, and the extensor brevis digitorum tendon is sutured to a previously-made bone hole which is located at the radial side of the proximal phalanx of the thumb through a subcutaneous tunnel. The tension of the transplanted muscles should be adjusted appropriately.
   (b) Management of vessels at the receipt site. Isolate the radial artery at the wrist level, and observe the blood supply after temporary occlusion of blood flow with vascular clamps. Insufficient blood supply means that this artery cannot be ligated but can only be anastomosed end to side. Then the cephalic vein and dorsal subcutaneous vein was exposed.
   (c) Vessels and nerve anastomosis. The radial artery-dorsalis pedis, cephalic vein-dorsocuboidal vein are anastomosed in an end to end fashion under a microscope. The branch of nervi peronaeus profundus is anastomosed to the recurrent branch of median nerve.
   (d) Incision closure. After thorough washing of incision and hemostasis, a full thickness skin graft harvested from the abdomen is used to close the incision. Skin and subcutaneous tissue at the donor site incision can be sutured directly. The ankle joint should be under plaster fixation in a neutral position for 3 weeks.

14.6.1.1 Transfer of Pedicled Abductor of the Fifth Finger Muscle

A female with injury to the left median nerve at the axillary region (18 months after injury) received transferring of pedicled abductor of the fifth finger muscle for functional reconstruction of thumb abduction and opposition.

Origin: transverse carpal ligament.

Insertion: the dorsal radial side of the head of the first metacarpal (Fig. 14.9).

14.7 Functional Reconstruction for Brachial Plexus Injury

Generally, nerve repair can have little effect on functional recovery for delayed brachial plexus injury. Consequently, the residual muscles of less importance can be transferred to the dysfunctional ones which are responsible for more important function. The complexity and variety of brachial plexus injury usually lead to various protocols of muscle reservation, so accurate evaluation of the strength of the residual muscle is critical in functional reconstruction. For functional deficits due to brachial plexus injury, Moberg proposes the following key points: (1) stability of the scapula; (2) rotation function of the shoulders; (3) flexion of the elbows; (4) flexion of the wrists; (5) most importantly, grasp and prehension of hands, which means opposition function of the thumb and digits.

For upper brachial plexus injury, the primary goal is to reconstruct shoulder abduction and elbow flexion. Generally, transfer of the trapezius muscle is used for reconstruction of shoulder abduction. Transfer of the sternocostal part of pectoralis major, latissimus dorsi, pectoralis minor, and triceps brachii, and Steindler's flexorplasty can be used for elbow flexion reconstruction. For lower brachial plexus injury, the primary goal is the thumb opposition and digital flexion and extension. Therefore, only forearm muscles and tendons innervated by C5, C6, and C7 are preserved. Reconstruction procedures include, (1) brachioradialis transfer for flexor pollicis longus, (2) flexor carpi ulnaris transfer for flexor digitorum profundus, (3) extensor carpi radialis longus transfer for thumb opposition, and (4) Zancolli's operation. For total brachial plexus injury of more than 2 years in which muscle atrophy has developed, sternocleidomastoid can be transferred for elbow flexion which is the most important function of the upper limb.

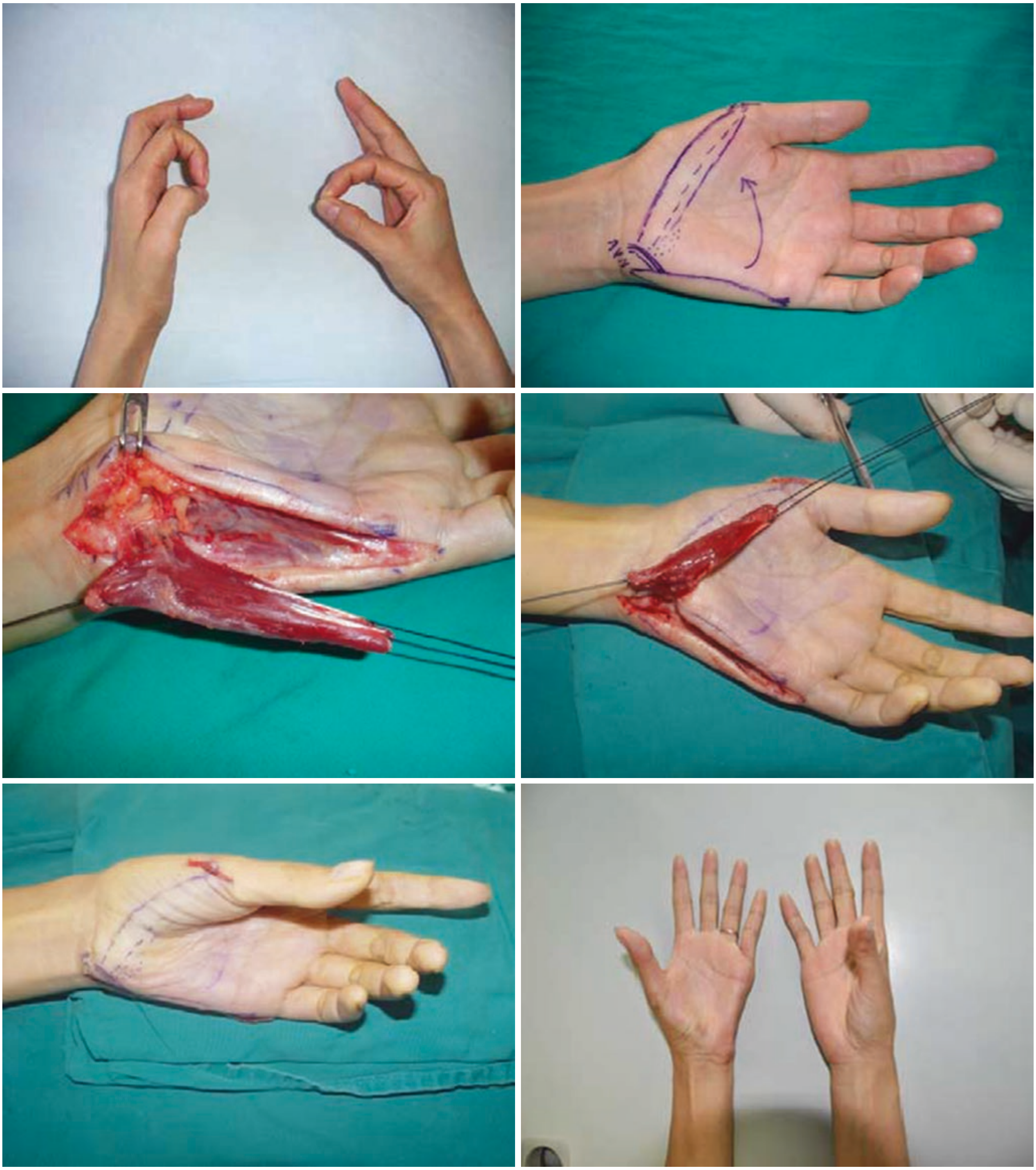

Fig. 14.9 Reconstruction of thumb abduction opposition function by bipolar abductor digitorum minimus transposition with vascular nerve pedicle

Fig. 14.9 (continued)

Muscle transplantation with anastomosis of nerves and blood vessels is an option for delayed brachial plexus injury. Notably, since Doi proposed the double muscle transplantation for hand function reconstruction in 1995 (two-staged operations for elbow flexion and digital movements respectively), the traditional view that free muscle transplantation can only be performed after failure of nerve repair (2–5 years after injury) has been changed. This deeply impacts the treatment of brachial plexus injury. Currently, nerve transfer combined with early double free gracilis muscle transplantation, as well as the contralateral C7 nerve root transfer via the anterior vertebral route to repair low trunk combined with free gracilis muscle transfer has been proved to be effective and promising for total brachial plexus root avulsion. For delayed upper brachial plexus injury, the above-mentioned methods in Sect. 14.2 can still be useful in reconstruction of shoulder abduction and elbow flexion. For delayed lower brachial plexus injury, the above-mentioned methods in Sects. 14.2 and 14.4 can also be useful in reconstruction of finger flexion and thumb opposition. Additionally, functioning free muscle transplantation can be used for elbow extension.

14.7.1 Nerve Transfer Combined with Early Double Gracilis Muscle Transplantation for Total Brachial Plexus Root Injury

This surgery integrates the advantages of Gu YD's multiple nerve transfer and Doi's free muscle transplantation. Nerve transfers which aim to regain preferable shoulder abduction, elbow extension, and hand sensory recovery are followed by early free double gracilis muscle transplantation which reconstructs elbow flexion, and extension and flexion of thumb and fingers. Specifically, (1) phrenic nerve transfer for suprascapular nerve in the first operation, (2) contralateral gracilis muscle transplantation for elbow flexion and digital and thumb extension (innervated by the trapezius branch of accessory nerve) in the first operation, (3) ipslateral gracilis muscle transplantation for thumb and digital flexion (innervated by the fourth, fifth and sixth intercostal nerves) in the second operation, (4) third intercostal nerve transfer to the triceps brachial branch of radial nerve for elbow extension, (5) transfer of the sensory branches of the third, fourth, fifth and sixth intercostal nerves to the lateral part of median nerve for hand sensation in supplementary operations, and (6) infusion of the metacarpophalangeal joints.

1. In the first stage, via the surgical approach for brachial plexus exploration, the external jugular vein and transverse cervical artery are anastomosed with the nutrient vessels of the transplanted muscles, respectively. The phrenic nerve is dissected and anastomosed with the suprascapular nerve for abduction reconstruction. If the phrenic nerve is not available, the contralateral C7-sural nerve grafts are chosen.

   The first-staged contralateral gracilis muscle transplantation (powered by the trapezius branch of accessory nerve) is used for elbow flexion, and thumb and digital extension.
2. In the second stage of operation, via the mid-axillary line approach to identify the lateral branch of intercostal nerve, the main trunk of the intercostal nerve is dissected until between the anterior axillary line and the midclavicular line, including the third, fourth, fifth and sixth intercostal nerves with an average length of 10–12 cm. After the mid-axillary line incision is extended in a Y-shaped way, the lateral portion of median nerve and the triceps branch of radial nerve are dissected and cut off. The motor branch of the third intercostal nerve is anastomosed with the triceps branch of radial nerve. The fourth, fifth and sixth intercostal nerves are anastomosed with the lateral portion of median nerve.

After the ipsilateral gracilis muscular flap is harvested, it is placed at the medial side of upper limb. The proximal side is fixed at the second and third rib. The motor nerves of the muscle are anastomosed with the fourth, fifth and sixth intercostal nerves without tension. The nutrient artery of the muscle is anastomosed with the brachial artery in an end-to-side fashion and the vein of the muscle is anastomosed with the deep brachial vein(s) in an end-to-end fashion. Guide the muscle through the subcutaneous route to the distal portion of the forearm, and then flex the elbow by 45°, and flex the wrist or fingers to adjust the muscles' tension. The muscles' tendon is weaving sutured with flexor pollicis longus and flexor digitorum profundus together. After the operation, immobilize the limb at the elbow flexion and forearm adduction.

Recently, the phrenic nerve can also be harvested under arthroscopy and anastomosed with the motor nerve of the muscle so as to reconstruct thumb and digital flexion. In this case, the muscular flap can be placed at the distal part of the upper limb, with the new origin fixed at the septum of intermuscular brachii medialeta.

3. Postoperative management. (1) Immobilization for 4–6 weeks. (2) Expansion of blood vessels, observation of flap circulation, and intervention of the ischemic crisis (in less than 4–6 h). (3) Using drugs to promote nerve regeneration, such as immune suppressor FK506. (4) Rehabilitation: Passive motion of the elbow and hand starts 4–6 weeks after operation, and active motion begins 3–4 months after operation, and voluntary exercise and anti-resistance exercise start 6–8 months after operation.

14.7.2 CC7 Nerve Transfer Combined With Gracilis Muscle Transplantation for Total Brachial Plexus Root Injury

Contralateral C7 nerve root transfer is an important option for brachial plexus avulsion injury. Gu YD proposes that the contralateral C7 nerve transfer should be performed in two stages. Contralateral C7 nerve root transferred can also be a donor for the gracilis transplanted to establish elbow flexion and digital flexion. Mcguiness and Wang SF propose the contralateral nerve transfer should be performed via the route between esophagus and vertebral body to directly repair the upper or lower trunk, with or without sural nerve as an allograft. They believe the transfer via the pre-vertebral route can shorten the distance of nerve regeneration. Wang SF also investigated the feasibility to directly anastomose the contralateral C7 with the lower trunk in an attempt to shorten the distance of nerve regeneration. Gu L performed a clinical and anatomical study on contralateral C7 nerve transfer via the anterior scalene and anterior vertebral body route which shows that the anterior and posterior divisions of the contralateral C7 nerve root can be as long as 7.71 ± 1.16 and 6.97 ± 1.18 cm, respectively, indicating that the both can be guided through the anterior scalene and anterior vertebral body route to the contralateral side to directly repair the avulsed nerve root (C8 and T1 or C5, 6). Gu L proposes a surgical protocol for total brachial plexus injury in which the contralateral C7 nerve transfer is used (through the anterior vertebral route) to repair the lower trunk directly and combined with the gracilis muscle transplantation in the second stage.

14.7.3 Contralateral C7 Nerve Transfer (Through the Anterior Vertebral Route) to Repair the Lower Trunk in the First Stage

1. Indications: definite diagnosis of total brachial plexus injury by clinical examination, MRI, or CTM; avulsion of C7, C8, and T1 accompanied with C5 and C6 rupture; duration between primary injury and surgery was less than 12 months.
2. Surgical procedures
   (a) Exploration of the brachial plexus. Via the transverse approach above the clavicle, the nerve root is dissected and explored, for confirmation of the avulsion of C8T1 root or lower trunk. In some cases in which the nerve roots or lower trunk retract to underneath the clavicle or the scar tissue extends to the clavicle posteriorly and inferiorly, exploration underneath the clavicle is recommended. In the position of shoulder flexion and adduction, identify the target nerve roots and guide them to the anterior scalene muscle for use.
   (b) Harvest of contralateral C7 nerve root. Via the transverse approach above the clavicle, the C7 nerve root is dissected to the intervertebral foramen and identified. The nerve root is dissected distally until the portion where the lateral cord and posterior cord start so that the C7 nerve root can be harvested as long as possible.
   (c) Directly repair the lower trunk using the contralateral C7 nerve root. The anterior border of anterior scalene muscle and the lateral border of C6 and C7 vertebrae are exposed. The surgeon then uses the index finger to do blunt dissection between the vertebral and esophagus until the ipsilateral side, and then uses a large curved forceps to guide a hose from the contralateral side via the prepared route to the other side. The contralateral C7 nerve root is guided to the deep of scalene anterior through the space medial to scalene anterior which is accommodated for the

index finger before the C7 nerve root is placed in the hose. Draw the hose to guide the contralateral C7 nerve root to the other side (1–3 cm beyond the incision). In the position of shoulder flexion and adduction, the transferred C7 nerve root is anastomosed with C8T1-lower trunk without tension. The 'splint' fashion of nerve anastomosis is applied to relieve the tension, and 9–0 sutures are used for perineurium anastomosis.

3. Key points. With the development of CTM and MRI, early diagnosis of brachial plexus injury is possible, and further early surgical inspection and repair is possible in 1–2 months after injury. In an early stage after injury when the hyperplastic tissues and scars are light, it is more convenient to perform surgical intervention than in a late operation (3 months after injury). In an early operation, it is easy to pull and guide the nerve root. This is favorable for direct repair of contralateral C7 nerve root.

   Microsurgical dissection at the portion where the anterior and posterior cords start helps increase the length of nerve harvested. A sufficient length of contralateral C7 nerve root is favorable for anastomosis without tension.
   Immobilization is necessary to avoid anastomosis failure due to motion of the patient's head during recovery from anesthesia. The immobilization should be continued for 6 weeks.

   Free gracilis muscle transplantation for elbow flexion and thumb and digital flexion in the second stage is the same as described in the first stage operation.

14.7.4 Functional Muscle Transplantation for Lower Brachial Plexus Root Injury

The lower brachial plexus injury (BPI) is uncommon compared with upper and total BPI. There are few methods to repair C8-T1 avulsions, and the outcomes are not satisfactory. The ulnar nerve, medial brachial cutaneous nerve, medial antebrachial cutaneous nerve, median nerve and partial radial nerve are often involved in lower BPI, resulting in severe dysfunction or even loss of hand function, but the functions of shoulder, elbow and wrist was are usually preserved. The sensory deficits are commonly located at the ulna side of the forearm and hand.

Nerve transfer and free muscle transplantation are two procedures commonly used in clinic. Gu Y successfully reconstructed thumb and finger flexion by transferring the brachialis muscle branch of the musculocutaneous nerve (BMBMCN) to the posterior part of the median nerve in treatment of C8T1 avulsions. Nagano A et al. transferred the intercostal nerve to the median nerve or ulnar nerve, and Doi et al. transplanted free gracilis muscle to reconstruct thumb and finger flexion with the intercostal nerve as the donor nerve.

Gu [3] reported using free gracilis muscle transplantation to reconstruct thumb and finger flexion for lower BPI with BMBMCN as the donor nerve in two patients. Their 2 years' follow-up revealed that patients regained noticeable improvement in digital flexion, with the muscle power of M4. In addition, transection of BMBMCN did not cause functional impairment to the elbow or the wrist. The muscle power of the elbow flexion was similar to the preoperative level.

1. Surgical methods

   Free gracilis muscle transplantation innervated by the brachialis muscle branch of the musculocutaneous nerve for reconstruction of thumb and finger flexion.

   (a) Anesthesia: general anesthesia.
   (b) Preparation for the recipient site. A 15-cm longitudinal incision is made in the medial-inferior part of the medial upper extremity. After skin and subcutaneous tissue are incised to expose the basilic vein, median nerve and biceps, the median nerve and biceps are retracted laterally to expose the brachialis, brachial artery and musculocutaneous nerve (MCN). The MCN is dissected carefully to expose the brachialis branch which should be definitely identified by observing contraction of brachialis due to electrical stimulation. Another 7-cm longitudinal incision is made in the distal part of the forearm near the wrist, and skin and subcutaneous tissue are incised to expose the tendon of flexor digitorum profundus and flexor pollicis longus muscle. Finally, a subcutaneous tunnel between the two incisions is made for placement of the gracilis tendon.
   (c) Harvest of gracilis muscle flap, as described before.
   (d) Free gracilis muscle transplantation to reconstruct thumb and finger flexion. The gracilis muscle flap is placed above the elbow, with the proximal site of muscle anchored to the medial brachial intermuscular septum. The distal tendon is then woven into the flexor digitorum profundus and flexor pollicis longus tendons using a Pulvertaft weave. The vascular anastomosis is performed under a microscope; with the artery and vein of the gracilis anastomosed to the brachial artery and basilic vein, respectively. The gracilis motor nerve is sutured with BMBMCN using 9–0 nylon sutures with the assistance of microscope.

2. Postoperative protocol. After surgery, the upper extremity is immobilized by plaster for 6 weeks.
3. Outcomes. In the present study, free gracilis muscle transplantation was used to reconstruct thumb and finger flexion with BMBMCN as the donor nerve in two patients. After 2 years, the patients regained a noticeable improvement in digital flexion and a muscle power of M4

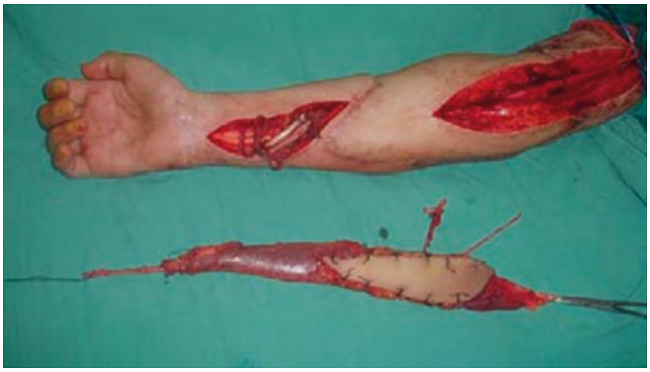

Fig. 10 Gracilis muscle transplantation with vascular nerve anastomosis for reconstruction of thumb abduction opposition function

(Fig. 14.10). However, a secondary surgery was still needed to reconstruct the sensation of the ulna side of the hand and function of the intrinsic muscle.

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