Nerve Reconstruction

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Keywords

Peripheral Nerve Injuries • Nerve Reconstruction • Principles of nerve repair • End-to-end repair • End-to-side-neurrorhaphy • Nerve grafting • Vascularized nerve grafting • Brachial plexus injuries • Avulsion plexopathies • Nerve Transfers

Introduction

Until the late eighteenth century it was believed that peripheral nerves did not regenerate after injury. Introduction of microsurgical techniques [1] in peripheral nerve surgery and the establishment of the principle of tension free repair [2] allowed inspired surgeons such as Narakas, Millesi, Allieu, Brunelli, Terzis, Doi, Gu, and others to suggest several new approaches to nerve reconstruction.

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Many factors influence the success of nerve repair and reconstruction. The age of the patient, the timing of nerve repair, the level of injury, the extent of the zone of injury, the technical skill of the surgeon and the method of repair contribute to the functional outcome after nerve injury. The basic tenets of nerve repair continue to hold true, including an accurate preoperative assessment, properly timed and executed exploration, meticulous nerve repair and intensive postoperative re-education [3].

As soon as nerve injury occurs, its target muscles begin to undergo atrophy and lose their motor end plates. Expedient diagnosis and testing is the best means of maximizing functional return. An adequate and properly timed treatment of peripheral nerve injuries is crucial to achieve a reasonable satisfying clinical outcome, although a complete nerve injury always will lead to varying degrees of permanent dysfunction in adults.

The aim of this chapter is to review the principles and techniques of nerve reconstruction and to discuss the options of repair including direct repair, nerve grafts, end-to-side neurorrhaphy

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and nerve transfers following nerve injuries in the upper extremity.

Background – Aetiology

The hand has been called an extension of the brain, and the sensory and motor performance of the hand is based on adequate function of components in the peripheral as well as the central nervous system. From a hand surgery perspective, poor functional outcomes after peripheral nerve lesions represent a frustrating problem.

Injuries to peripheral nerves are common in all forms of upper extremity trauma but management of them remains a challenge. Common causes include lacerations, fractures, dislocations, ligamentous tears, crush and amputation injuries. Injuries are most often caused by domestic or industrial accidents or interpersonal violence. Nerve injuries range from nerve compression lesions, like carpal tunnel syndrome, up to severe rupture and avulsion of spinal nerve roots of the brachial plexus (BP). Males suffer traumatic nerve injuries at a ratio of 2.2:1 compared with females [4]. The typical patient who sustains a nerve laceration is a male in his late teens or early twenties.

As a protective instinct, the arm, forearm and hand are frequently outstretched during injury. The upper extremity therefore often absorbs the initial impact, with the dominant arm involved slightly more frequently. The most frequently injured nerves are the radial nerves of the index finger, the ulnar digital nerves of the small finger, and the median and ulnar nerves at the wrist level [5].

As far as BP injuries are concerned, high-velocity motor vehicle accidents account for the majority of the cases; most studies report that motorcycle accidents are responsible approximately twice as often as automobile accidents. Nerve injuries in these cases are from traction and compression, with traction accounting for 95 % of injuries. Other common causes include (in different percentages according to different studies) industrial accidents, pedestrian vehicle accidents, snowmobile accidents, gunshot wounds, and other penetrating injuries [6].

Only around 3 % of hand injuries include injury to peripheral nerve trunks. Even a minor injury to a finger causing a digital nerve injury (incidence 6.2/100,000 inhabitants/year) may induce dysfunction of the hand. The consequences of a median or ulnar nerve injury in the forearm are even more wide-ranging for the patient. The injury does not only cause problems in the patient's professional life but leisure activities are also severely impaired.

The overall incidence of BP injuries in multitrauma patients secondary to motor vehicle accidents ranges from 0.67 to 1.3 % [7]. This number increases to 4.2 % for victims of motorcycle accidents. This difference can easily be explained by the increased forces applied to the BP of the unprotected body during a high velocity motorcycle accident.

Presentation

Pathophysiology

Following peripheral nerve injury, morphologic and metabolic changes occur. Within the first few hours to days, morphologic changes occur in the corresponding neurons, including swelling of the cell body, displacement of the nucleus to the periphery, and disappearance of basophilic material from the cytoplasm, a phenomenon termed chromatolysis.

Within 2–3 days of injury, edema forms in the axonal stumps and the distal stump undergoes Wallerian degeneration. This degenerative process is called Wallerian degeneration after Augustus Waller, who first characterized morphological changes in the distal stump of sectioned frog glossopharyngeal and hypoglossal nerves 160 years ago [8]. During Wallerian degeneration, Schwann cells from the distal stump proliferate, help inflammatory infiltrating cells to eliminate debris, and upregulate the synthesis of trophic (factors which support neuronal survival and axonal growth) and tropic (factors which influence the growth direction of the regenerating axons) factors. The Schwann cells, close to the site of transection, go through the same type of changes as the Schwann cells in the distal nerve segment.

After 3–6 weeks, endoneurial tubes are left behind that consist of basement membranes lined with Schwann cells which proliferate and organize into columns, guiding the regenerating axonal sprouts within the basement membranes to their targets. In the gap between the proximal and distal nerve segment an inflammatory response occurs and a fibrin matrix, filled with macrophages, is formed. Schwann cells can migrate from both ends where the migration of such cells takes part in concert with the outgrowing axons. Metabolic changes within the neuronal cell body involve switching the machinery normally set up to transmit nerve impulses to manufacturing structural components needed for reconstruction and repair of the damaged nerve.

End organs also undergo changes after nerve injury. Complete atrophy occurs within 2–6 weeks of denervation. Fibrosis occurs in motor fibers at 1–2 years and fragmentation and disintegration occur by 2 years. It is generally agreed that functional recovery is diminished if the nerve does not reach the motor end-plate by 12 months. Sensory end-organs are less sensitive to denervation than motor end-organs. It has been shown that recovery of protective sensibility is possible even after many years from nerve injury [9] but that the degree of functional sensation decreases the longer the delay in nerve repair.

Classification of Nerve Injury

In 1941, Cohen introduced a classification to describe nerve injuries which was later popularized by Seddon [10]. According to this, there are three distinct clinical entities for a dysfunctional nerve: neurapraxia, axonotmesis or neurotmesis.

Neurapraxia, refers to a localized conduction block, is a comparatively mild injury, with motor and sensory loss but no evidence of Wallerian degeneration. The nerve distally conducts normally. Tinel's sign (a tingling sensation perceived distally when percussion is carried out over the injury site of a nerve which indicates involvement or in a partial lesion the commencement of regeneration as the nerve attempts to heal) [11]. The underlying mechanism is attributed to focal demyelination or ischemia. Recovery may occur within hours, days, weeks or up to a few months.

In axonotmesis the axons are ruptured, but the epineurium and perineurium remain intact. It is commonly seen after crush injuries. Wallerian degeneration does occur distal to the injury, but regeneration from the proximal stump is still possible. Functional recovery depends on the severity of the lesion and the degree of internal disorganization in the injured nerve as well as its distance to the end organ.

Neurotmesis describes the situation in which the entire nerve trunk is completely ruptured and axonal continuity can not be restored. Sharp injuries, some traction injuries or injection of noxious drugs are the most common causes. Prognosis for spontaneous recovery is extremely poor without surgical intervention.

In 1951, Sunderland [12] expanded upon Seddon's classification system by defining five distinct degrees of nerve injury. Sunderland's 3rd and 4th degree injuries were included as extensions of axonotmesis and neurotmesis respectively.

First degree injury (neurapraxia) is a localized conduction block with preservation of the nerves'anatomical continuity. Although recovery is complete, the time required varies from days to 3 months.

In second degree injury (axonotmesis) the endoneurium and the perineurium remain intact. A Tinel's sign is present. Wallerian degeneration occurs distal to the site of injury. Nerve recovery may be complete.

Third degree injury involves endoneurial scarring and disorganization within the fascicles. The endoneurial tube is disrupted, resulting in erroneous alignment of the regenerating fibers. An advancing Tinel's sign indicates the level of regeneration, but the degree of recovery will not be complete.

In fourth degree injury the nerve is in continuity, but regeneration does not occur across scar block. A Tinel's sign is found at the level of the injury, but does not advance further. It is commonly caused by severe stretch, traction, crush, cautery injury or nerve injection. Surgical intervention is necessary.

In fifth degree injury there is severance of the nerve trunk. Recovery is not possible without surgical intervention. This lesion is associated with penetrating trauma.

Preoperative Investigation and Diagnosis

The formulation of a diagnosis, treatment plan, and prognosis can be largely accomplished by means of a careful and detailed history and physical examination. The timing of the injury will help guide treatment recommendations, which the mechanism gives clues about the severity of the lesion.

The examination of passive range of motion of all joints of the affected extremity should be done and recorded before examination of active range of motion. All the upper extremity muscles have to be tested and compared to corresponding ones on the contralateral normal side. The grip and pinch muscle strength are measured using a Preston dynamometer set on intermediate position. The sensory evaluation should include the supraclavicular area, the arm, the forearm, and the hand. Color and trophic changes of the arm should be observed. For evaluation of sensibility in the hand, static and moving two-point discrimination (needs to take place with the patient sitting across from the examiner and having the eyes closed), Semmes-Weinstein monofilament pressure testing or von Frey cutaneous pressure threshold testing, testing for perception of high- and low-frequency vibration, and ninhydrin testing should be performed.

A detailed history of pain, its onset, duration, quality, sharpness, and radiation is routinely recorded. The results are recorded on a BP chart (Fig. 1.1) which includes all muscle groups of the

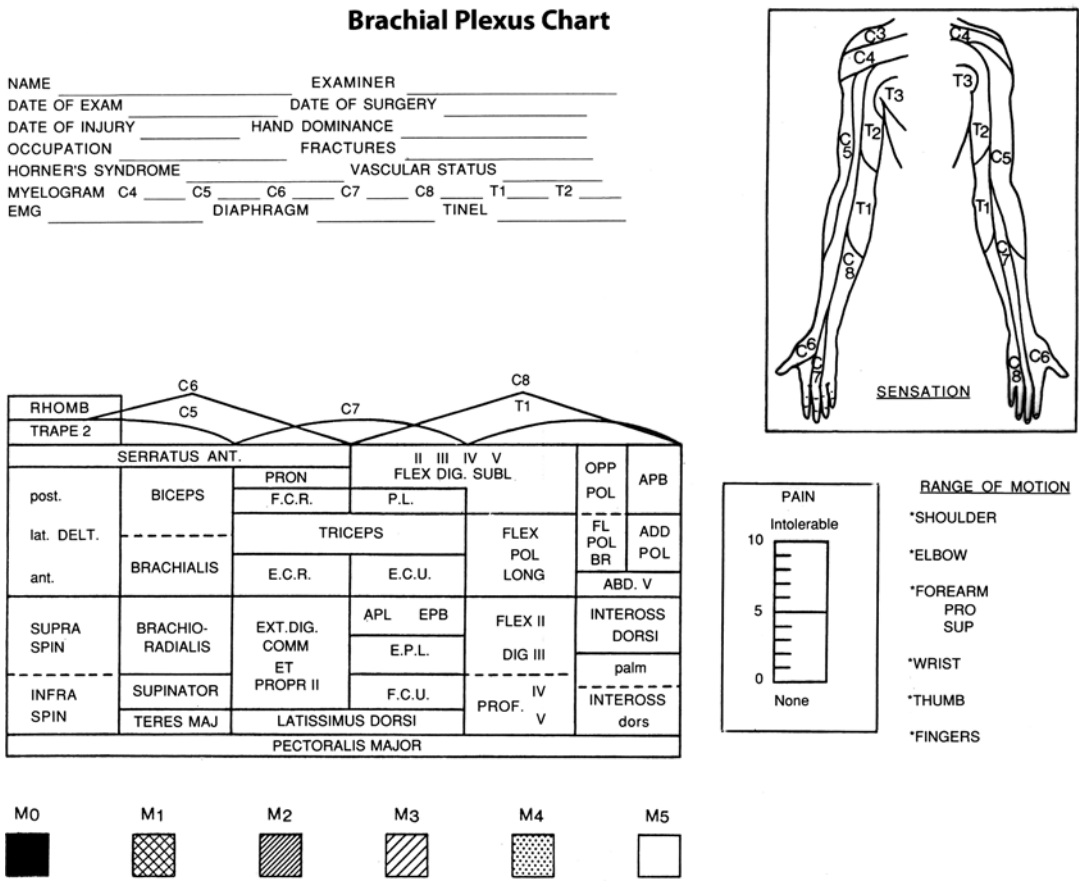


Fig. 1.1 Preoperative brachial plexus chart

upper extremity, sensory mapping, and pain level. This is important not only for the initial visit, but also to document and follow clinical recovery after repair.

The British Medical Research Council grading scale is used by most physicians. This system has been further modified by Terzis [13] with intermediate grades of (+) and (−).

In cases of BP injuries, the presence of Horner's sign is a strong indicator of avulsion of the C8 and T1 roots. Moreover, the absence of a Tinel's sign in the supraclavicular area is a strong indicator of root avulsion and is a bad prognostic sign because it indicates lack of intraplexus donors for reconstruction. On the other hand, a positive Tinel's sign is a strong indicator of roots connectivity with the spinal cord.

The initial electrodiagnostic evaluation of the upper extremity should include needle electromyography and nerve conduction studies. Axonal discontinuity results not only in predictable pathologic features but also in time-related electrical changes that parallel the pathophysiology of denervation. Wallerian degeneration results in the emergence of spontaneous electrical discharges for at least 3 weeks after the injury. Therefore, a needle electromyogram should be postponed for at least that long and preferably carried out at 6 weeks.

The lamina test is performed in cases of adult BP injuries. Tiny volleys of electrical stimulation are applied at the level of each foramen on each exiting root to determine whether the patient perceives the area of the dermatome innervated by this root. A positive response would be strong evidence against avulsion.

Depending on the mechanism of injury and the location of the nerve lesion, radiologic imaging may be necessary to confirm or support a diagnosis of a nerve injury. In cases of BP injuries, imaging studies (such as myelography, CT myelography, and magnetic resonance imaging) are used in order to detect abnormalities of the nerve roots (such as traumatic pseudomeningocele, deformity of nerve root sleeves, dural scar, and nerve root avulsion). A combination of myelography with computed tomography of the cervical spine is used to identify root avulsions (Fig. 1.2). In case of previous vascular injury and subsequent reconstruction, angiography should be employed to investigate the blood supply of the extremity and to identify any vascular compromise (Fig. 1.3).

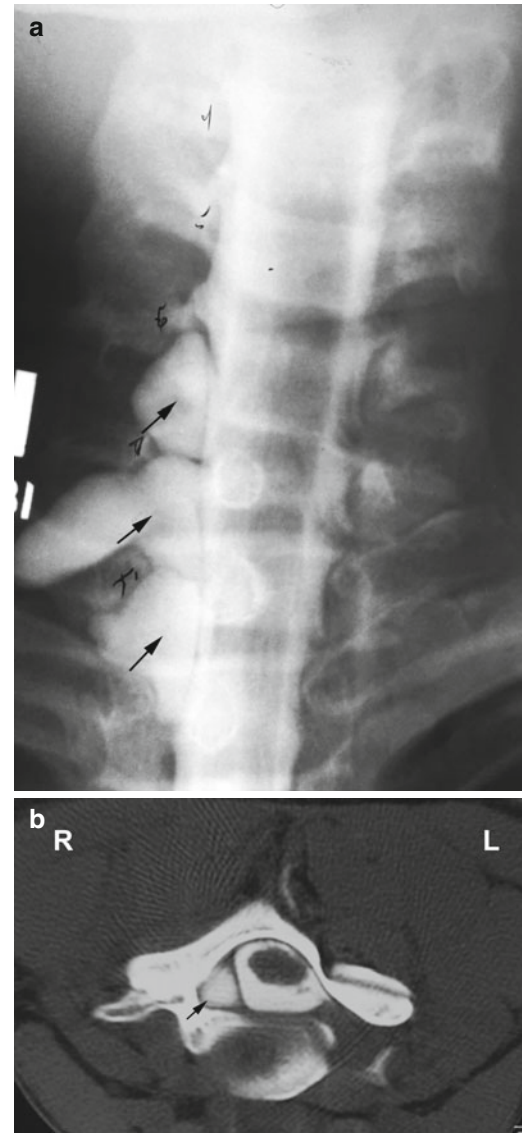


Fig. 1.2 CT Myelography showing root avulsion. (**a**) Myelography of the Cervical spine in a patient with multiple root avulsions (*arrows*). (**b**) Example of CT myelography in a patient with severe right brachial plexus injury. Note avulsed root on the right (*arrow*)

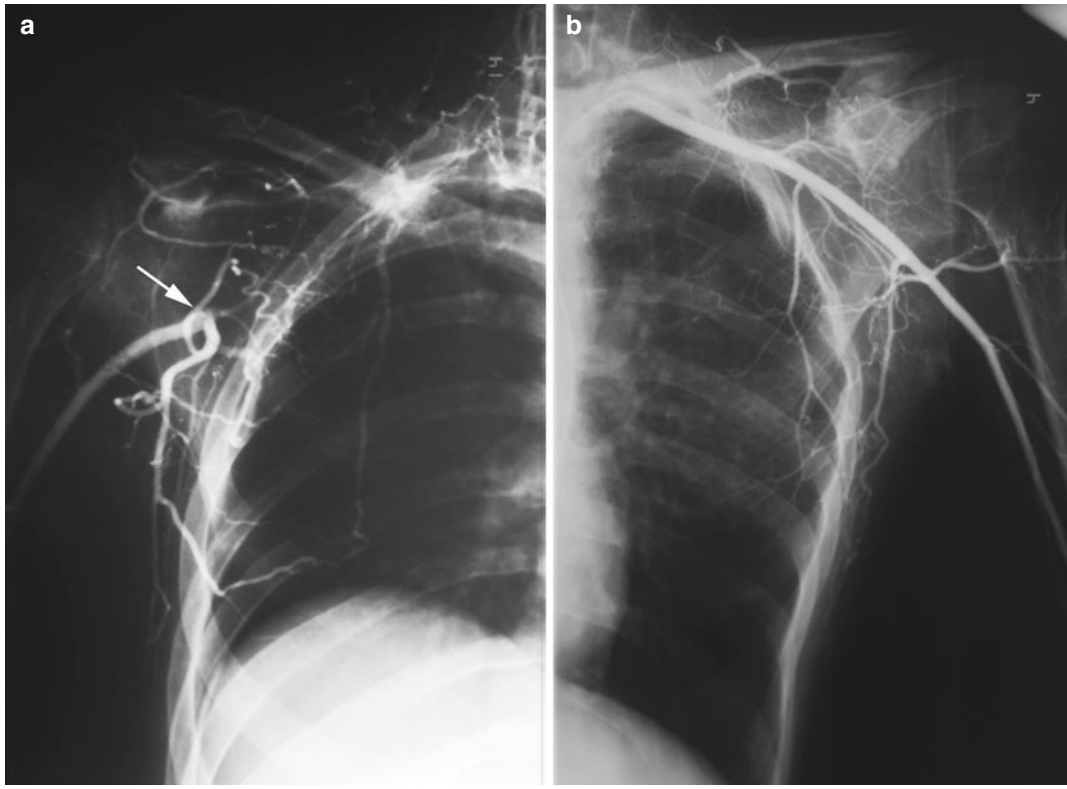


Fig. 1.3 Angiography of upper extremity in cases of vascular injury. (**a**) Angiography of right upper extremity. Note interruption of (*R*) subclavian artery (*arrow*). Axillary artery receives flow from collateral vessels. (**b**) Normal angiography of left upper extremity

Treatment Options

Principles of Nerve Repair

The basic principles of nerve repair include a sequence of eight basic principles that represent the basis of the microsurgical management of the nerve injured patient [14]:

1. Preoperative assessment of motor and sensory function
2. Adequate debridement of the proximal and distal nerve stumps in order to allow nerve regeneration to proceed across the repair site
3. Utilization of microsurgical techniques
4. Tension-free repair
5. When a tension-free repair is not possible, use of other techniques for nerve repair; nerve grafts, end-to-side nerve repair or nerve transfers
6. Primary repair; when this is not possible, delay repair for approximately 3 weeks when the 'zone of injury' is clarified
7. Utilization of a nerve repair technique that allows early protected range of motion to permit nerve gliding
8. Occupational and physical therapy in order to maximize the clinical outcome

Timing of Nerve Repair

A primary nerve repair is defined as reconstruction shortly after the injury. Secondary repair is defined as occurring at a later period after injury. Several investigators have reported that nerve repair is better when performed within 6 weeks of injury and several studies have shown primary repair to be superior to secondary repair as long as the tissue bed is adequate [15, 16].

In general, nerve injuries associated with open wounds require early exploration except from gunshot wounds, which are more appropriate to be treated as closed or blunt trauma. In crush nerve lesions or injuries associated with

significant soft tissue damage it can be difficult to estimate the extent of the zone of injury. In these cases, a delayed repair, after 3 weeks, is indicated, when the zone of injury becomes better demarcated and the extent of scar tissue can be easily defined.

In closed or blunt trauma, initial management is expectant with close observation. If complete recovery is not observed within 6 weeks, electrodiagnostic studies should be obtained for baseline evaluation. If at 12 weeks complete recovery has not occurred, repeat electrodiagnostic studies should take place. Presence of increase of motor units potentials in electromyography is an indicator that spontaneous reinnervation most likely will follow. Lack of signs of reinnervation (clinical or electrical) at 12 weeks post injury requires surgical exploration.

BP injuries are worth specific consideration regarding the timing of exploration and reconstruction. Such injuries require extra care since BP injuries usually come with other associated injuries including fractures, vascular injuries and associated soft-tissue injury. Although exploration of the BP injury may need to be performed with a slight delay, the modern management of BP injuries is early aggressive microsurgical reconstruction [17].

Techniques of Nerve Repair

In general, nerve exploration and repair should be performed under high magnification of the operating microscope. Exploration always takes place proximal and distal to the lesion site until normal nerve to inspection and palpation is encountered. If the history and physical examination is suspicious of double level injury then the entire length of the nerve needs to be explored. The ideal scenario for nerve repair is end-to-end coaptation of the nerve stumps.

The procedure of repairing a nerve trunk can be divided into four steps. After the zone of injury is defined, the nerve endings are cut back to healthy fascicles. Then, the nerve ends are approximated keeping in mind the importance of considering the length of the gap and possible tension at the coaptation site. If additional nerve length is required, releasing constricting fascia, dividing adventitia attachments, dissecting any tethering bands, transposing nerves (e.g. ulnar at elbow) and flexing neighboring joints (e.g. wrist for median and ulnar lesions in Zone 5) will mobilize the nerve further. Tensionless repairs have demonstrated superior results. Exceeding 10 % of the resting length of the peripheral nerve has been shown to decrease blood flow to the nerve by 50 % [18]. Tension is assessed intraoperatively to determine the need for grafting. A good rule of thumb is that if nerve ends can be approximated with 8-0 sutures, then grafting is not required.

The next step is the correctly aligned coaptation of the nerve ends. Last step is the maintenance of nerve repair with microsutures (9-0 or 10-0 nylon) which are inserted into the epineurium. Placement of the sutures should avoid malrotation of the nerve ends.

Epineurial repair has been shown to have similar functional results to group fascicular repair in smaller, more distal nerves [19]. Group fascicular repair is preferred in larger nerves where motor and sensory fasicles can be accurately matched (most notably the ulnar nerve below the elbow). The cross-sectional appearance of the proximal and distal stumps should be carefully inspected under high magnification prior to proceeding with the nerve repair.

The accuracy of nerve apposition at the repair site influences the functional restoration. Presently, anatomic axon-to-axon reconnection and normal restoration of function after significant nerve injury remain an unobtainable goal. Electrophysiologically-aided motor- and sensory- fascicle differentiation has been an important tool that facilitates our ability to depict the intraneural composition of sensory and motor bundles prior to nerve coaptation [20]. In 1976, Williams and Terzis [21] introduced single fascicular recordings as an intraoperative diagnostic tool for the management of peripheral nerve lesions in continuity which was a new method of sophisticated intraoperative differentiation between motor and sensory components.

Several histochemical methods have been developed to permit differentiation of motor and sensory fibers. The enzyme carbonic anhydrase

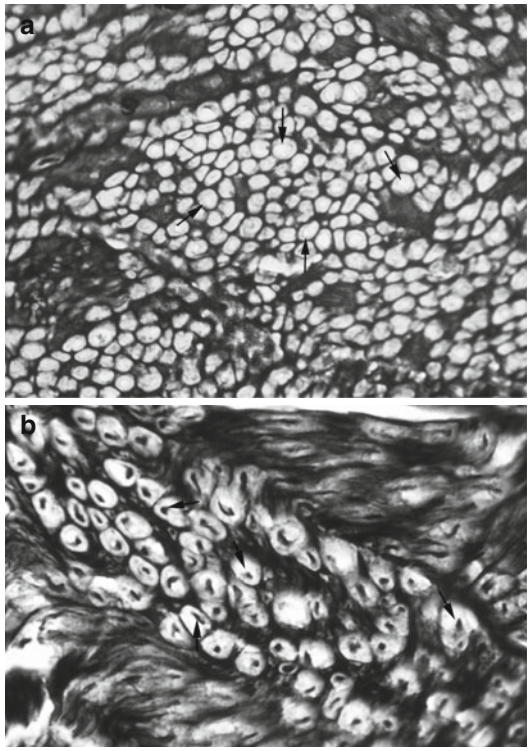


Fig. 1.4 Example of Carbonic Anhydrase staining. (**a**) Cross section of a motor fascicle. Note lack of axonal staining with the carbonic anhydrase (*arrows*). (**b**) Cross section of a sensory fascicle. Note dark staining of the axons (*arrows*)

can differentiate between motor and sensory fascicles of peripheral nerves [22] (Fig. 1.4). The application of this staining method to human peripheral nerve was first described by Riley and Lang in 1984 [22] and later modified for widespread clinical use by Carson and Terzis in 1985 [23]. Although it can provide a convenient method for identifying predominantly sensory versus motor fascicles in cut ends of peripheral nerves, its use depends on the surgeon's experience, available operating time and existence of an experienced laboratory in nerve histochemistry. Acetylcholinesterase histochemistry was also used in conjunction with peripheral nerve surgery, this enzyme in contrast to carbonic anhydrase, is present only in motor fibers [24].

End-to-End-Repair

The surgeon should be familiar with the various techniques available and tailor them to the situation, taking into account which nerve is injured and the level of the injury in the upper extremity. The basic choices include epineurial repair, group fascicular repair, fascicular repair or a combination of those techniques. The goal is to achieve tension free coaptation and proper alignment.

In the epineurial repair, coaptation is achieved by single epineurial stitches in the epineurium along the circumference of the nerve. A perfect superficial alignment can be achieved using epineurial vessels as landmarks, but the internal orientation of fascicular bundles and individual fascicles may not be correct. This method is indicated when one or only few fascicles are injured and is appropriate for distal nerve repairs (digital nerves).

In group fascicular repair, fascicular groups are coapted with single sutures in the perineurium or perifascicular connective tissue which surrounds groups of fascicles. Prior to coaptation, the fascicular groups need to be identified and matched together. In large nerves with multiple fascicles, nerve regeneration can be enhanced by use of this technique.

In fascicular repair, coaptation of individual fascicles is achieved by 10-0 or 11-0 microsutures in the internal epineurium surrounding individual fascicles. This type of repair is not feasible unless it can be performed with minimal tension.

End-to-Side Nerve Repair (Fig. 1.5)

The idea of end-to-side nerve repair was popularized by Viterbo et al. in 1992 [25] after its introduction a century ago [26]. This technique allows for additional muscle reinnervation with minimal detriment to donor-nerve function [25]. Using this technique a neurorrhaphy is created between the proximal end of an injured nerve and the side of an uninjured donor nerve by simple microsurgical attachment at the site of a window (epineurial and/or perineurial window).

The efficacy of end-to-side neurorrhaphy has been established in several rat models. Noah et al. [27] suggested that more axons went through the coaptation site when a perineurial window or partial neurectomy was created in the donor-nerve prior to coaptation vs leaving the perineurium or epineurium intact. Okajima et al.

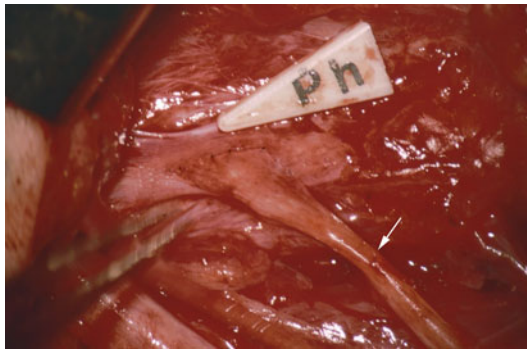


Fig. 1.5 Example of end-to-side nerve repair. Example of an end-to-side neurorrhaphy in an obstetrical brachial plexus case. An epineurial and perineurial window has been made on the phrenic nerve. An interposition nerve graft (*arrow*) is coapted by end-to-side repair at the site of the window. The nerve graft is targeted to neurotize the musculocutaneous nerve (not shown). Because an end-to-side coaptation was used there is no downgrading of the function of the ipsilateral diaphragm

[28] studied the early regenerative response after end-to-side neurorrhaphy and were able to identify increased nodal sprouting proximal to the perineurial window and/or partial neurectomy groups vs the intact epineurium group.

In clinical practice, Terzis [29] used end-to-side neurorrhaphy extensively in order to minimize morbidity from the various extraplexus donors. Thus, only the number of donor fibers needed are taken, such as in partial phrenic or partial hypoglossal transfers, which are used in combination with an end-to-side coaptation via an interposition nerve graft especially in cases of facial paralysis and obstetrical BP reconstruction.

Nerve Grafting (Fig. 1.6)

When tension-free repair is not possible, a suitable alternative must be pursued. The surgical technique employed in these alternatives is similar, whether it be a nerve graft or nerve transfer.

Nerve grafting has long been considered the 'gold standard' for repair of irreducible nerve gaps. The choice of autogenous graft is dependent on several factors: the size of the nerve gap, location of proposed nerve repair, and associated donor-site morbidity.

Before grafting, the proximal and distal nerve stumps must be prepared to normal tissue outside of the zone of injury. In cases of polyfascicular nerve stumps, interfascicular dissection is preferred in order to prepare corresponding fascicular groups. The intraneural topography of both nerve stumps is obtained by means of intraoperative electrodiagnostic studies and carbonic anhydrase histochemistry.

Then, the defect size is measured and the nerve grafts are harvested. The nerve grafts are then tailored so that they bridge corresponding fascicular groups. The proximal end of each graft is coapted to the proximal fascicular group and its distal end to the corresponding distal bundles.

Selection of the graft donors is limited by the availability of donor nerves and the functional and aesthetic deficits created by their harvest. According to Sunderland and Roy [30] the ideal donor-nerve should possess the following characteristics:

1. the sensory deficit should occur in a non-critical area of the body
2. the donor-nerve should possess long, unbranched segments
3. the donor-nerve should easily be accessible and reliably located
4. the donor-nerve should be of overall diameter and possess large fascicles with little interfascicular connective tissue and few interfascicular connections

The commonly used donor-nerves available for grafting are typically the sural nerve, the saphenous nerve, the medial brachial cutaneous nerve and the lateral antebrachial cutaneous nerve.

Vascularized Nerve Grafts (Fig. 1.7)

The first vascularized nerve graft in the upper extremity was a pedicled nerve graft in 1945 by St. Clair Strange for reconstruction of large nerve defect: the ulnar nerve was transferred in two stages to reconstruct the median nerve [31]. Taylor et al. [32] used the superficial radial nerve as a vascularized nerve graft, to repair a large defect of a median nerve.

In 1984, Breidenbach and Terzis [33] defined the blood supply of peripheral nerves that could be used for microvascular transfer and introduced a classification of the blood supply of nerves

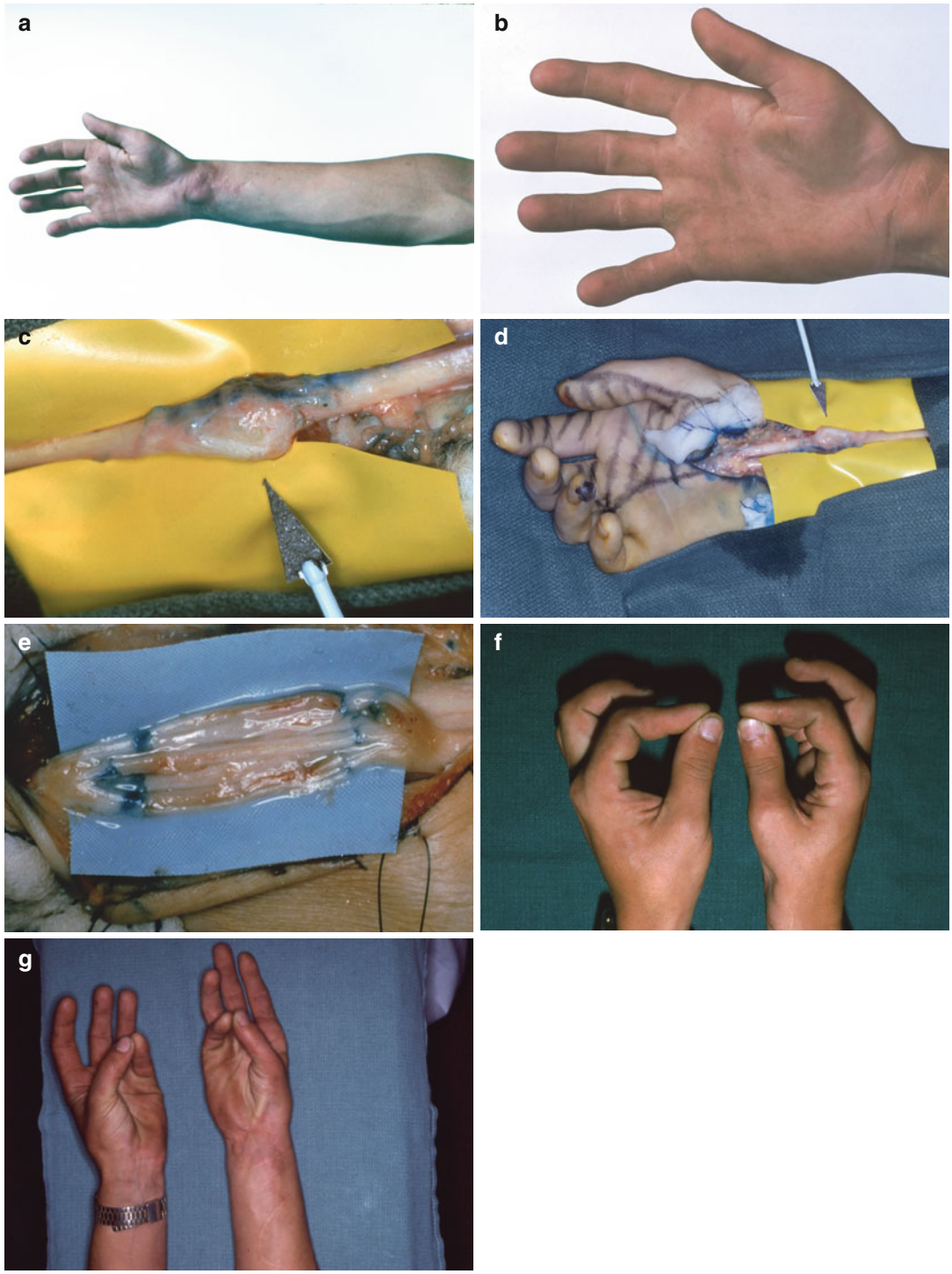


Fig. 1.6 Example of a case treated with interposition nerve grafting. A 19 year old boy was involved in an accident in which he sustained a glass laceration of the volar aspect of his right dominant wrist. He presented 18 months later to our Center with complete anesthesia of the thumb, index and radial side of the middle finger and had no thumb opposition (**a**, **b**). On exploration, a large median nerve neuroma was present (**c**, **d**). The neuroma was excised and the defect was reconstructed with five interposition sural nerve grafts (**e**). Eight months later, he also had opponensplasty which involved transfer of the sublimis tendon from the ring finger to the thumb to augment opposition. Upon follow-up the patient showed adequate pinch (**f**) and strong thumb opposition (**g**). Sensory return to the radial side of his hand has been satisfactory, enabling him to return to his previous work

based on the number of dominant vascular pedicles.

The clinical indication for a vascularized nerve graft is a scarred recipient bed that will not support a nonvascularized nerve graft. In cases of long gaps, vascularized nerve grafts can be placed in association with nonvascularized nerve grafts to cover the cross-sectional area of the injured nerve. The obvious advantage of this technique is the ability to provide immediate intraneural perfusion in a poorly vascularized bed and to reconstruct large nerve defects.

The use of vascularized nerve grafts is particularly important in BP surgery. In cases of avulsion of the C8 and T1 roots, the ulnar nerve should be used as a vascularized nerve graft for ipsilateral plexus reconstruction or as a cross-chest nerve graft from the contralateral C7 root for neurotization of the denervated upper extremity [34] (Fig. 1.8).

Breidenbach and Terzis [35] first reported that the ulnar nerve can be transferred in its total length on the superior ulnar collateral vascular pedicle (Fig. 1.9). Terzis subsequently reported a series of 151 vascularized ulnar nerve grafts for posttraumatic BP palsy patients [34]. According to this study, pedicled or free vascularized ulnar nerve grafts achieved superior results compared to those obtained with conventional nerve grafts.

Technique

Using this technique, the ulnar nerve with its supplying vascular pedicle is transferred as a pedicle or free vascularized nerve to bridge several nerve defects. The vascular pedicle is anastomosed to an artery and a vein of the recipient site and subsequently the nerve coaptations take place. The vascularized ulnar nerve graft is folded into segments maintaining their vascular connections according to the technique proposed

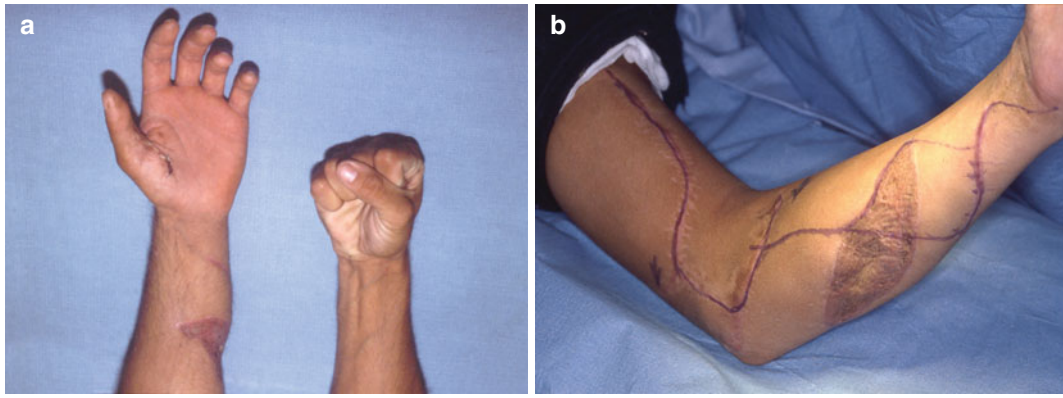
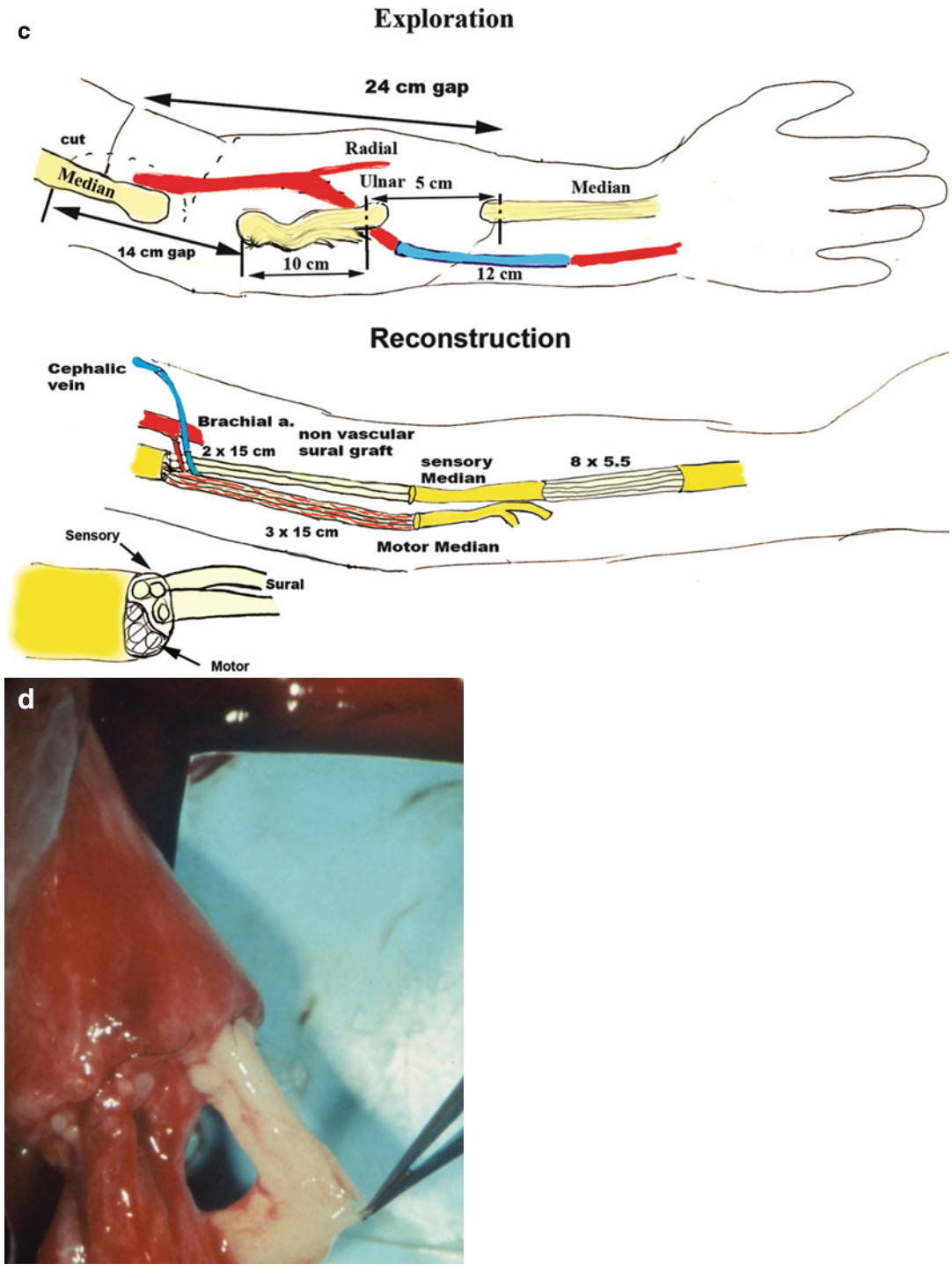


Fig. 1.7 Example of a case with Vascularized Nerve Grafts. This is a 23 year old male who was involved in a boating accident in which the propeller of a motor boat ran over his left arm. He was taken emergently to a local hospital where he was noted to have severe neurovascular injuries as well as tissue loss of the left forearm. He received elsewhere emergency revascularization of his left extremity with the use of saphenous vein grafts. He also had multiple levels of nerve injuries of the left ulnar and median nerve. Preoperative view of the patient (**a**, **b**). Three months later, he underwent reconstruction of his left median nerve which was transected at four levels (**c** above). The sensory part of the superficial and deep peroneal nerves based on their common vascular supply was harvested and used to reconstruct the motor portion of the median nerve (3 × 15 cm, one deep and two superficial peroneal nerve grafts). Nonvascularized sural nerve grafts were used to reconstruct the sensory portion of the median nerve (2 cables × 15 cm proximally and 8 cables × 5.5 cm distally: **c** below). Close-up of the proximal coaptation: vascularized nerve grafts on the left, nonvascularized sural nerve grafts on the right (**d**). Seven months after the injury he underwent reconstruction of the left ulnar nerve utilizing vascularized saphenous nerve graft (1 cable × 30 cm) for the motor portion of the ulnar nerve and sural nerve graft for the sensory component of the ulnar nerve (**e**). Four years postoperatively, we can see very good results. Powerful finger flexion, thumb opposition, and intrinsic function (**f–i**). He can easily pick up a can of soda (**j**) and has never had any morbidity in the donor extremity (**k**) (Requested permission from: Terzis and Kostopoulos [67])



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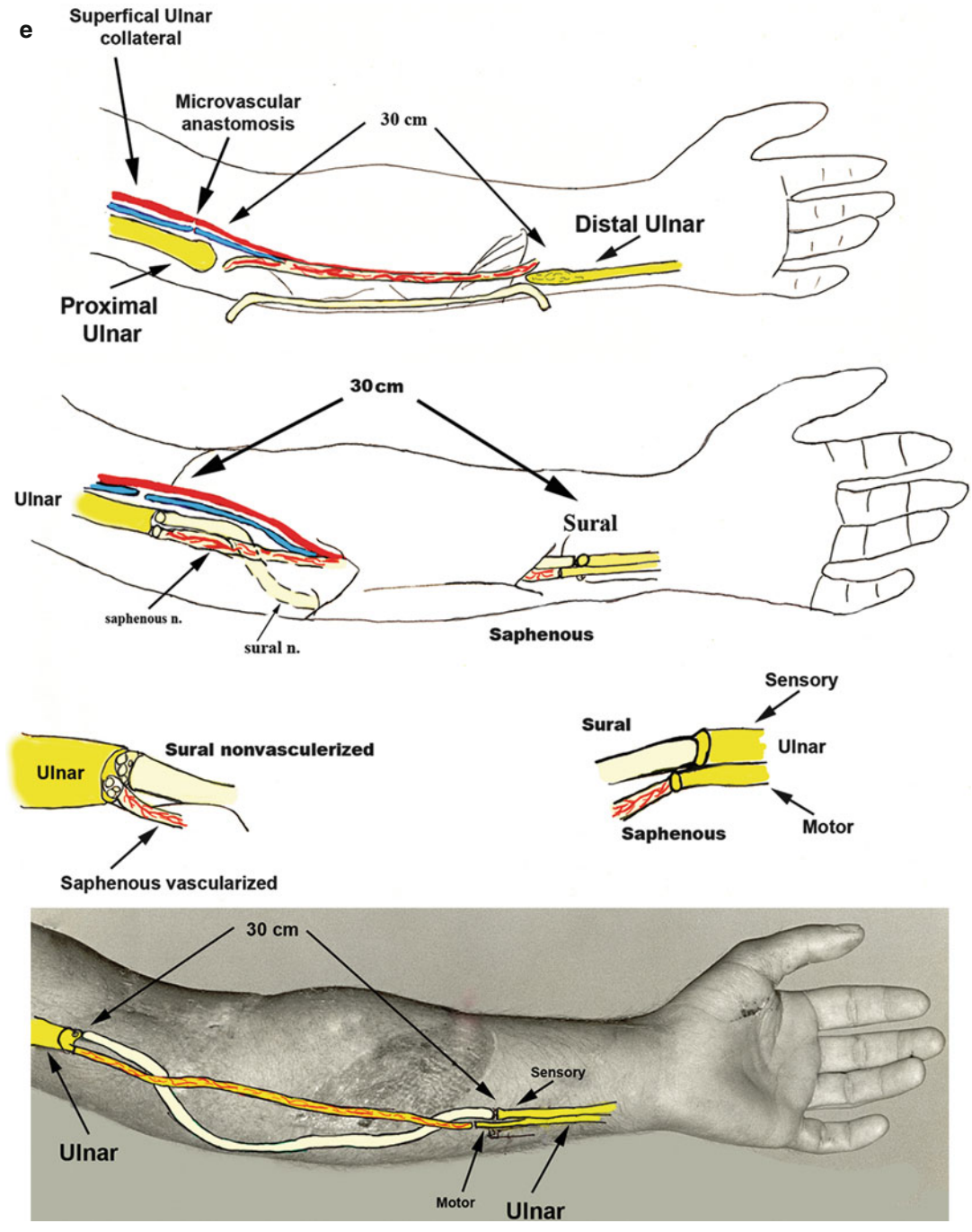

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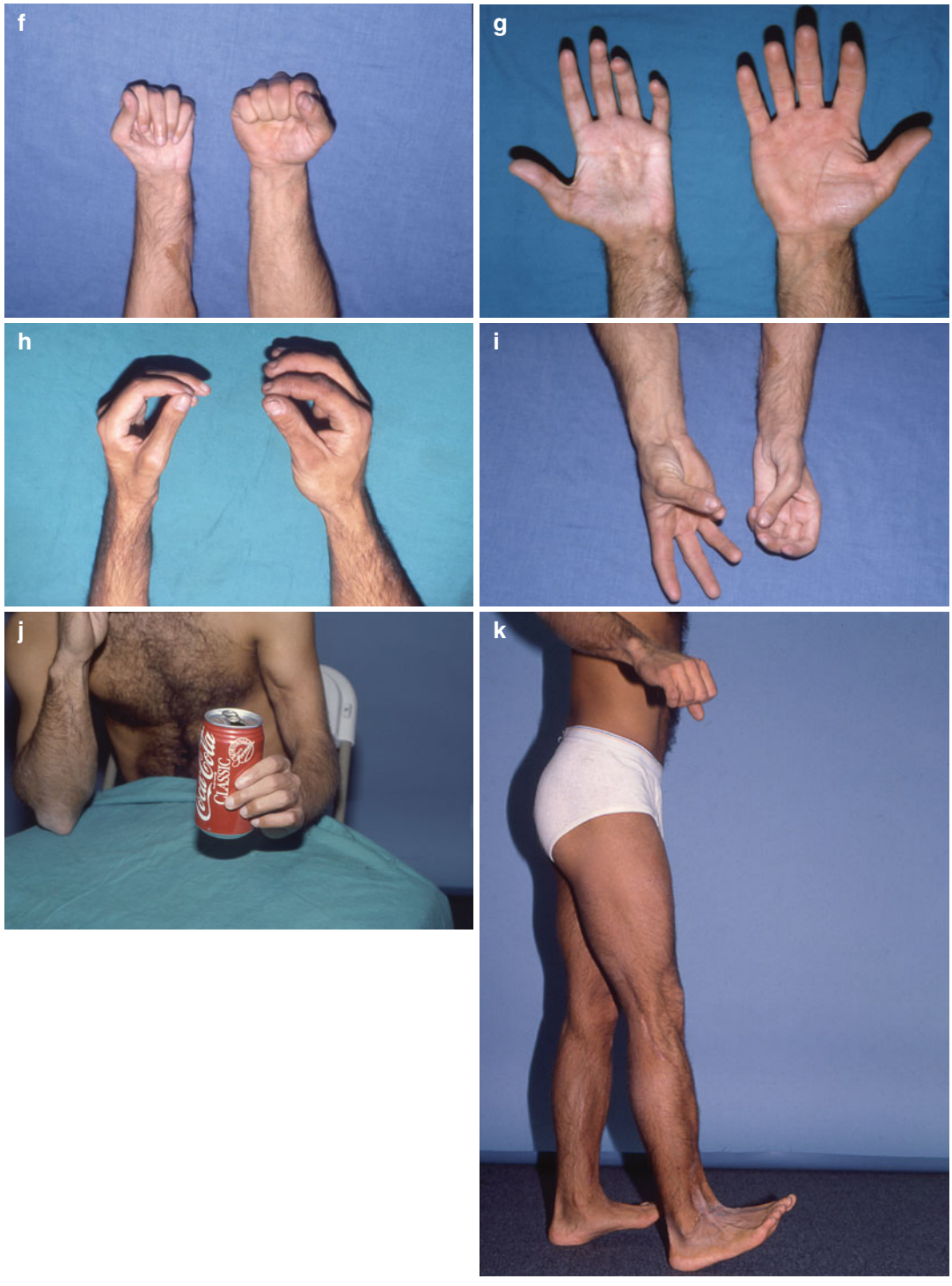

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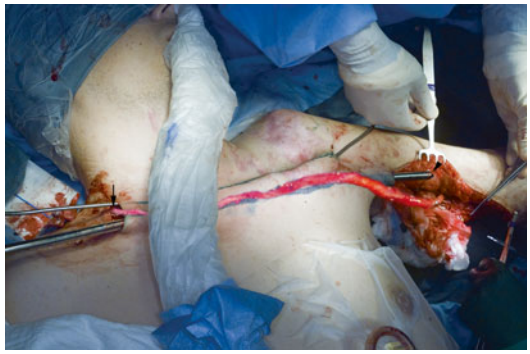

Fig. 1.8 Example of a cross chest vascularized ulnar nerve graft. Cross chest vascularized ulnar nerve graft prior to tunneling. The proximal ulnar will be coapted to the anterior division of the right C7 root. The distal ulnar nerve will be coapted to the median nerve of the left paralyzed extremity. *Arrow* points to the metal "passer" that will be used to transfer the nerve across the chest

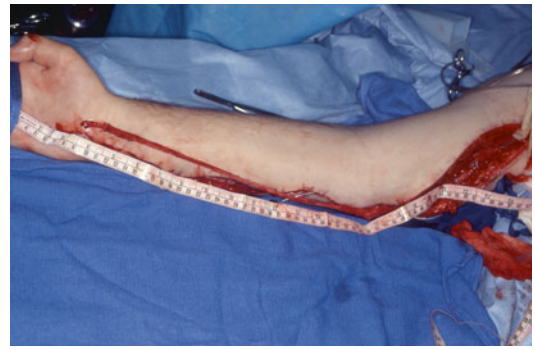

Fig. 1.9 Example of ulnar nerve harvested as a VNG next to the arm. Exploration of the right vascularized ulnar nerve graft prior to microvascular transfer. The entire length of the nerve receives its blood supply from the superior ulnar collateral vascular pedicle. Terzis' method for the use of the free vascularized ulnar nerve for ipsilateral intraplexus reconstruction. The epineurium is transected longitudinally without compromising the longitudinal epineurial blood supply and the fascicles are transected transversely. The blood supply is maintained through the folded epineurium

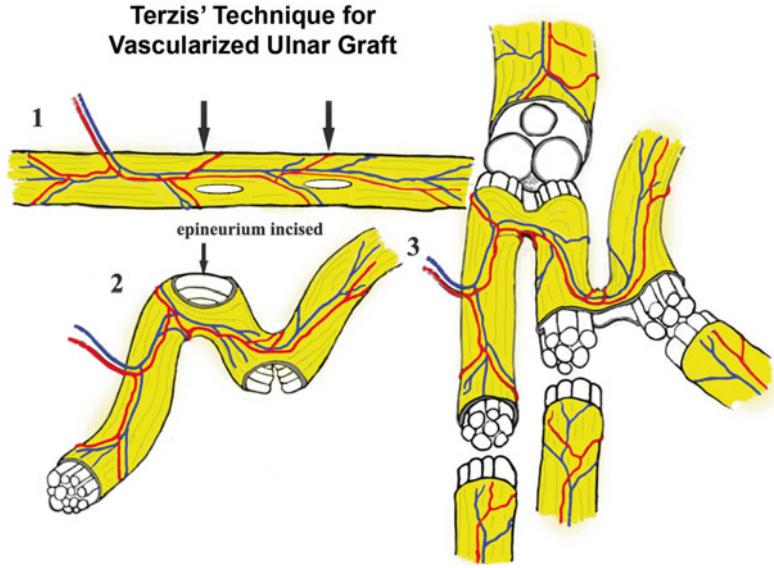

Fig. 1.10 Terzis' technique of using the vascularized ulnar nerve for ipsilateral BP reconstruction. Terzis' technique of folding the vascularized ulnar nerve graft into segments while maintaining its blood supply by preserving the integrity of epineurial vessels

by Terzis and Kostopoulos [34] (Fig. 1.10). In this situation, the longitudinal blood supply of the epineurium of the ulnar nerve is preserved while the intraneural contents are transected to address the bridging nerve defects, thus maintaining excellent blood supply throughout the vascularized ulnar nerve graft. In more distal lesions, vascularized fascia can be used to improve the blood supply of the underlying bed by enveloping the nerve reconstruction (Fig. 1.11).

Ulnar Nerve

Cases of global plexopathy with avulsion of the lower roots and rupture of the upper roots provide the best indication for using the ipsilateral ulnar as a vascularized graft for BP reconstruction. The ulnar nerve can be harvested on the superior ulnar

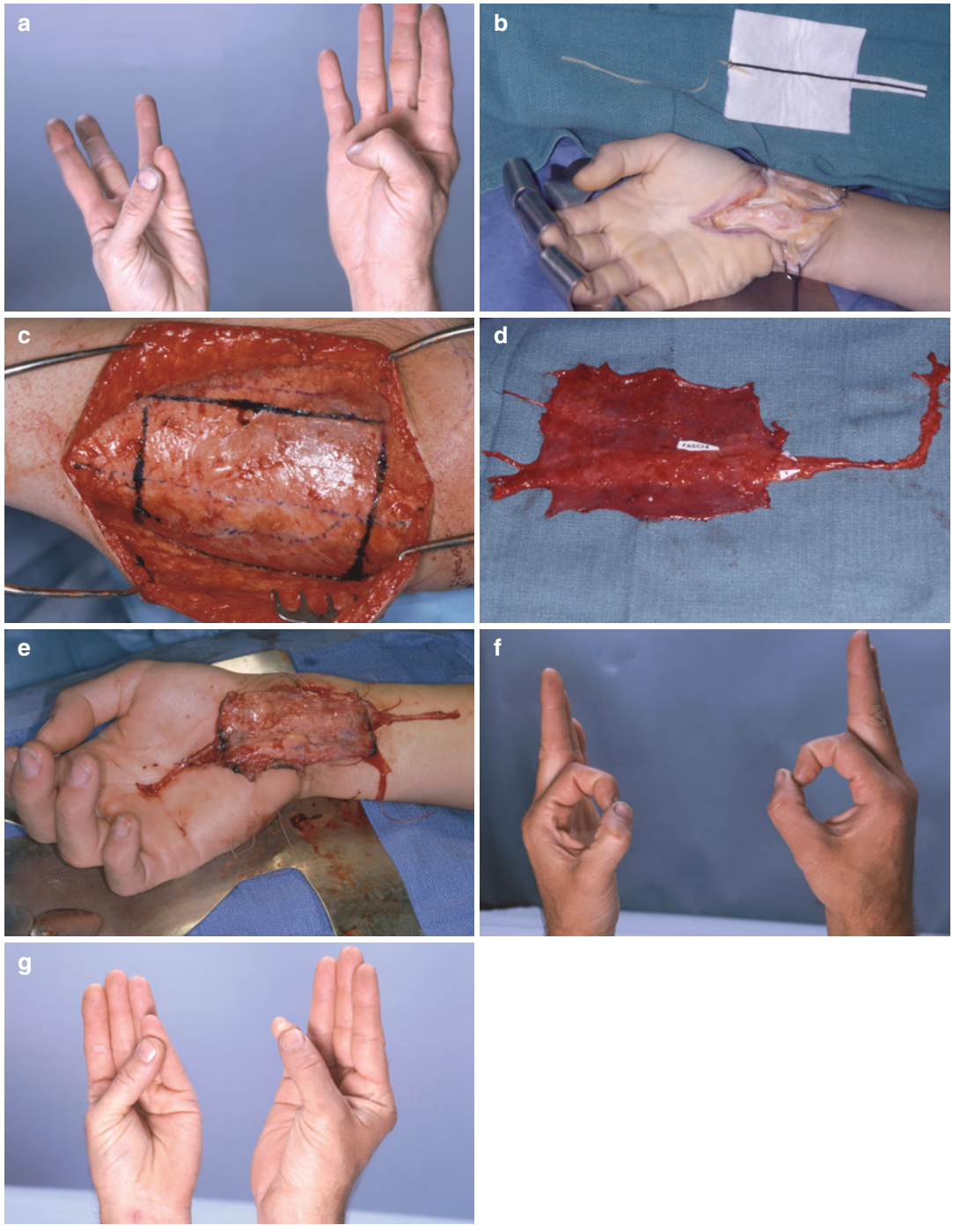

Fig. 1.11 Example of a vascularized fascia to improve the blood supply of nerve grafting in an unfavorable recipient bed. (**a**, **b**) Patient with right carpal tunnel syndrome and pain secondary to severe crush injury of the right distal forearm and hand. Note lack of opposition of the right thumb (**a**). Upon exploration a large neuroma in continuity of the median nerve was apparent (**b**). Extensive microneurolysis under high magnification of the operating microscope took place along with the transfer of a vascularized posterior calf fascia to envelop the nerve at the wrist. (**c**) The vascularized posterior calf fascia has been outlined in the non-dominant lower extremity. (**d**) The vascularized fascia flap after harvesting. (**e**) The vascularized fascia on the right wrist prior to microvascular anastomoses. (**f**, **g**) On the last follow-up, note excellent pinch and opposition. In addition, the patient is pain free and has returned full time to his job as a jeweler

collateral vascular pedicle. The superior ulnar collateral artery is sufficient to maintain the blood supply for the total length of the ulnar nerve (Fig. 1.9).

If used for ipsilateral BP reconstruction, the nerve is transected in the appropriate segments to bridge the nerve defects always preserving the epineurial blood supply (Fig. 1.10).

If used for neurotization of the median nerve from the contralateral C7 (cC7) root then the nerve is harvested as a free vascularized cross-chest graft (Fig. 1.8) and the superior ulnar collateral vascular pedicle is anastomosed to the transverse cervical vessels of the unaffected side prior to nerve coaptations of the proximal ulnar end with the anterior division of the cC7. Subsequently, the distal part of the ulnar nerve is coapted to the median nerve on the affected side.

Sural Nerve

Vascularized sural nerve graft for extremity nerve reconstruction should be used as a free vascularized nerve graft based on the sural artery, if available, or with an arterialized saphenous vein that is transferred in conjunction with the sural nerve (Fig. 1.12).

Saphenous Nerve

For BP injuries, the indications are the same as use of vascularized ulnar. Moreover, it can be used for more distal injuries when multiple major nerves are injured or the nerve gaps are too long.

Clinical Pearl – Ideal Donor Nerve

the sensory deficit should occur in a non-critical area of the body

the donor-nerve should possess long, unbranched segments

the donor-nerve should easily be accessible and reliably located

the donor-nerve should be of overall diameter and possess large fascicles with little interfascicular connective tissue and few interfascicular connections

Nerve Transfers

A nerve transfer recruits redundant nerve fascicles from a donor nerve to innervate critical motor or sensory nerves close to their target end-organs. Traditionally nerve transfers in the upper extremity have been used for BP injuries where there are limited proximal intraplexus motor donors. However, nerve transfers lately are starting to be used for a variety of peripheral nerve injuries.

According to Dvali et al. [36] the indications for nerve transfers in the upper extremity are:

1. BP avulsion injuries
2. Proximal nerve injuries which require a long distance for regeneration
3. Major limb trauma with associated loss of nerve tissue
4. In patients with long denervation time or in older patients
5. Avoidance of re-exploring an area of previous injury because of potential damage to critical structures

The ideal motor donor nerve should carry a large number of axons and be near to the denervated target. Moreover, it is preferred for a motor donor nerve to have limited donor-site morbidity and to innervate synergistic muscles.

According to Rosenfield et al. [16] the advantages of nerve transfers are:

1. There is preservation of muscle structure due to the fact that reinnervation must be made prior to 18 months to avoid irreversible fibrosis
2. There is no need for nerve grafting in order to bridge the nerve gap and thus avoidance of its potential complications
3. Potential mismatching is avoided, as nerves with dedicated function are selected as donors (eg. the common digital nerve from the fourth webspace to the first webspace to provides sensation to the ulnar side of the thumb and radial side of the index finger).

Lesions in Continuity

Intraoperative Diagnosis and Treatment

The exact level, type, and extent of the nerve lesion can be accurately determined only during surgical

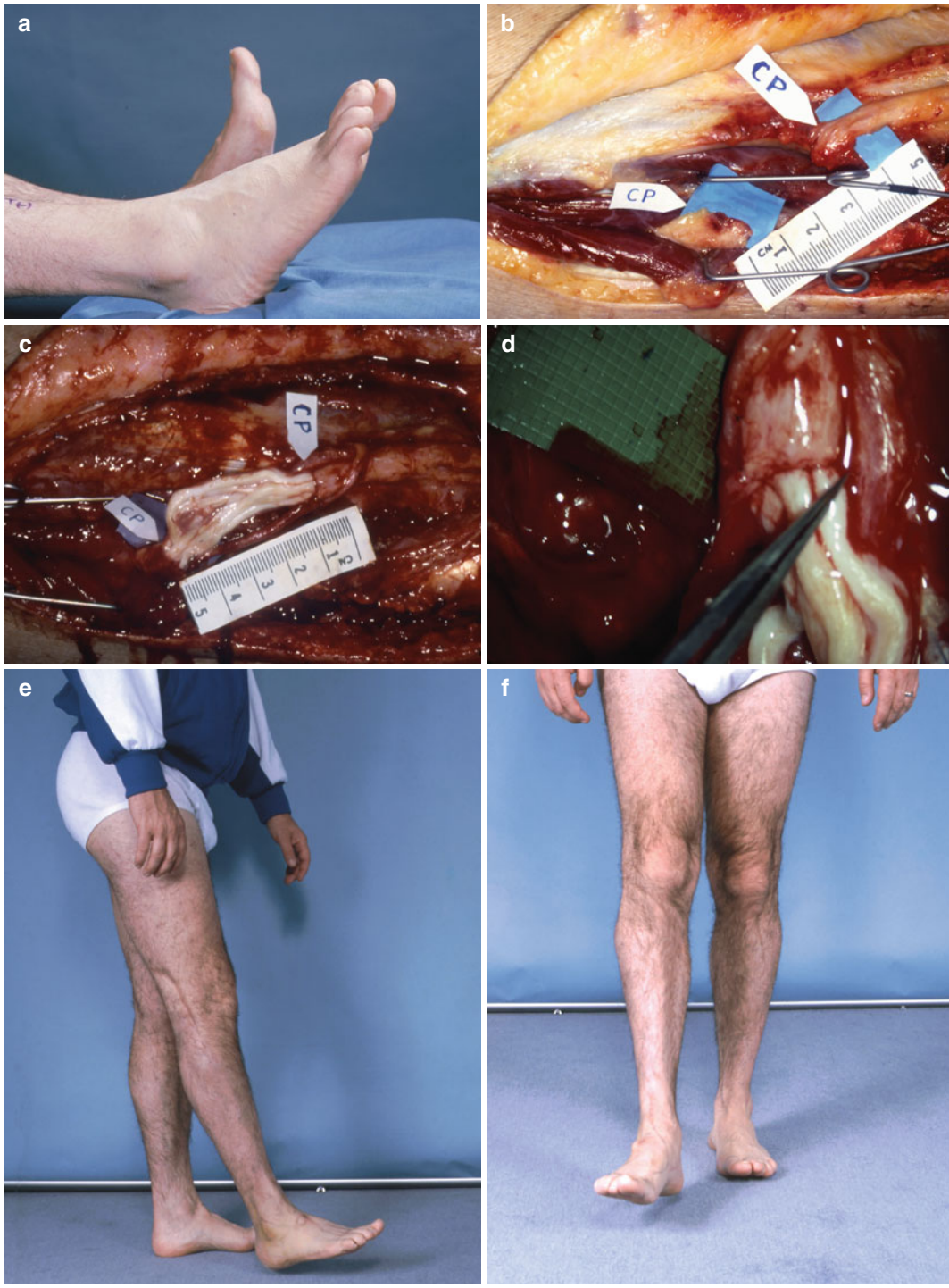

Fig. 1.12 Use of ipsilateral sural as a vascularized nerve graft for lower extremity nerve repair reconstruction. (**a**–**f**) A 41 year old male, who suffered a propeller injury and sustained a laceration at his right popliteal fossa. He presented to our Center with a right foot drop (**a**). Intraoperative view of the severed peroneal nerve stumps and the created five centimeter defect (**b**). Intraoperative view of the common peroneal nerve reconstruction using a combination of vascularized and nonvascularized sural nerve grafts (**c**, **d**). Patient at his last follow-up demonstrates excellent dorsiflexion of his right foot and is walking without a splint (**e**, **f**)

Clinical Pearls – Indications for Nerve Transfer

BP avulsion injuries

Proximal nerve injuries which require a long distance for regeneration

Major limb trauma with associated loss of nerve tissue

In patients with long denervation time or in older patients

Avoidance of re-exploring an area of previous injury because of potential damage to critical structures

exploration. Intraoperative electrophysiologic recordings are extremely important for providing direct evidence of the extent of neural injury. Intraoperative monitoring can be useful to facilitate the decision to repair, graft, or resect nerve tissue. However, while it does not substitute for preoperative electrodiagnostics, it is helpful to monitor nerve function, guide dissection, and identify neural from scar tissue [37].

Stimulating and recording electrodes are placed at least 5 cm apart on the nerve proximal and distal to the lesion respectively. A ground electrode is placed at the wound's edges. Then, compound action potential (CAP) are recorded across the injury site and displayed by a computerized device and disclose the degree of conduction across the tested nerve. The compound action potential will appear only if the nerve is functioning [20].

If a CAP is present, extensive neurolysis with or without interfascicular dissection takes place. If the nerve, following release of the constricting epineurium, still 'feels' hard to palpation, interfascicular neurolysis is performed. Intraoperative bulging of individual fascicles on release is a good prognostic sign, as it signifies that functional restoration will occur. Lack of bulging following interfascicular neurolysis is a poor indicator for recovery.

If a CAP is present but it is diminished in height and width and the nerve is in continuity but hard to palpation and after epineuriotomy and interfascicular dissection it is apparent that the perineurial integrity is lost in some of the fascicles but it is present in others, then under magnification, the involved fascicles should be resected and grafted, while the others, with perineurial integrity, should be preserved [21].

In cases where no CAP is recorded or there is no clinical evidence of sensory and motor function on preoperative assessment, interposition nerve grafts are used to reconstruct the injured nerve. In early cases (≤3 months) or secondary to sharp laceration injuries without appreciable loss of neural tissue, after proximal and distal mobilization of the nerve stumps an end-to-end epineurial repair is performed.

In cases of BP injuries, the presence of sensory action potentials and normal conduction velocities in a flail and anesthetic extremity implies root avulsion. Furthermore, intraoperative electrodiagnostic studies are useful in order to verify a suspected avulsion of a root or to determine whether resection of a neuroma and interposition nerve grafting should be performed.

An additional preoperative electrophysiological study for the investigation of patients with BP injury is the Lamina test, which was introduced by Liberson and Terzis [38] in 1987.

During this test, small volleys of electrical stimulation are applied on each exiting root to determine whether the patient perceives the area of the dermatome innervated by this root. A positive response would be strong evidence against avulsion.

Furthermore, the response of the vital signs of the patient to the resection of a neuroma can also indicate connectivity of the corresponding root to the spinal cord. If the vital signs of a lightly anesthetized patient rise suddenly during resection of the neuroma, this indicates that the root is in continuity with the spinal cord and not avulsed [17].

Terzis et al. [39] developed an intraoperative assessment measurement tool of the severity of a BP injury and labeled it 'Severity Score'. Each root, if intact, is given five points. A normal BP severity score equals 25. A globally avulsed BP has a score of 0. The lower the severity score, the worse the prognosis.

Avulsion of the BP roots always carries the worst prognosis and makes functional restoration in the paralysed upper extremity much more

challenging. A variety of extraplexus donors should be recruited in such cases to reconstruct the distal plexus elements [17].

One or Two Root Avulsions

(a) If the C5 and/or C6 are avulsed, reconstruction of the shoulder and elbow function can be achieved by means of:
   1. Distal spinal accessory nerve transfer to the suprascapular nerve
   2. If the three lower roots (C7, C8 and T1) are intact, intraplexus donors (ipsilateral C7, branch to the long head of the triceps) are used for biceps and deltoid neurotization. If the three lower roots are also ruptured, three intercostal nerves can be used for direct biceps neurotization.

(b) If the lower two roots (C8 and T1) are avulsed, C8 and T1 roots should be neurotized from C5, C6, or C7 in infants only. In adults, hand function is unattainable and thus the ulnar nerve can be harvested as a free or pedicled vascularized nerve graft in order to neurotize the musculocutaneous, axillary, median, and/or radial nerves [34, 40].

Three Roots Avulsion

(a) When the three upper roots (C5, C6, and C7) are avulsed, reconstruction is as follows:
   1. Distal spinal accessory nerve transfer to reconstruct the suprascapular nerve
   2. Intercostal nerves transfer for reconstruction of the axillary and the nerve to triceps. Fascicles of the ipsilateral ulnar nerve can be used for musculocutaneous nerve neurotization (Oberlin's transfer) [17, 41].

(b) If C7, C8, and T1 roots are avulsed, the force of this injury may affect the upper roots (C5, C6) as well, which may be ruptured. In such cases, the distal part of the accessory nerve is transferred to the suprascapular nerve whereas the ipsilateral ulnar nerve is used as a vascularized free or pedicled nerve graft to connect (in an end-to-end fashion) C5 and C6 roots with musculocutaneous, median, axillary, and/or radial nerves

Four Roots Avulsion

In BP injuries with four roots avulsion (C6, C7, C8, and T1), reconstruction is as follows:
   1. If the C5 root is well-developed (i.e. the BP is prefixed), the same reconstructive plan is used as with three root avulsions. If C5 is small, it is usually dedicated to neurotization of the musculocutaneous nerve via sural nerve grafts
   2. Distal spinal accessory nerve neurotises the suprascapular nerve
   3. Intercostals nerves are used for neurotization of axillary and triceps nerves
   4. Selective contralateral C7 root transfer [42, 43] is used as follows: The anterior division is coapted to a vascularized ulnar nerve graft for neurotization of the median nerve on the affected side while the posterior division is coapted to two saphenous cross-chest grafts which are 'banked' for future free muscles for hand reconstruction.

Global Avulsion

In case of global avulsion plexopathy, all reconstructions are carried out from extraplexus donors as follows:
   1. Transfer of the distal part of the accessory nerve to the suprascapular nerve
   2. Intercostals nerves are used for neurotization of axillary and musculocutaneous nerves
   3. Selective cC7 root transfer is used as follows: The anterior division is coapted to a cross-chest vascularized ulnar nerve graft for median nerve neurotization while the posterior division is coapted to two-cross-chest saphenous nerve grafts for triceps neurotization and as a 'banked' nerve for future free muscle for finger extension.

Surgical Techniques

Intraplexus Donors

The use of intraplexus motor donors is always preferred over extraplexus motor donors.

Intraplexus donors have a greater number of axons than the extraplexus donors and, when available, there is less need of postoperative reeducation. Generally, outcomes are superior if proximal healthy roots are available for neurotization of distal targets.

C5 Root Transfer

This is the strongest motor donor, and if there is no avulsion, the proximal part of the ruptured root can be used as a motor donor for multiple neurotizations with interposition nerve grafts. In normal conditions, the C5 root contains about 16,000 myelinated axons. If C5 is ruptured, but the proximal stump is in continuity with the spinal cord, with simultaneous lower root avulsions, then during the initial BP reconstruction, the ipsilateral ulnar nerve is used as a free or pedicled vascularized graft to reconstruct the musculocutaneous, the median, and, on occasion, the radial nerve.

Technique

The patient is placed in the supine position, with the head turned away from the operative side. A curved incision along the posterior border of the sternocleidomastoid muscle is carried out and the supraclavicular plexus is identified between the anterior and the middle scalenes muscles. The phrenic nerve is identified and stimulated in order to assess its integrity. Then, dissection proceeds posteriorly and the C5, C6 roots are identified.

Care should be taken to isolate the C5 root and preserve it, except in cases in which it is ruptured; in these cases, if the distal stump cannot be identified, the proximal stump should be used as a donor for neurotization procedures.

C7 Root Transfer

The selective ipsilateral or contralateral C7 root transfer for neurotization of high priority targets in BP reconstruction has been introduced by Terzis since 1991 [42, 43]. Due to extensive overlap among the nerve fibers derived from the upper and lower plexus, no single muscle of the upper extremity is solely innervated by the C7 nerve root [44]. The procedure involves extensive intraoperative mapping of the intact C7 root. Subsequently, the selective use of the anterior division fibers are targeted for contralateral flexor target neurotization while the posterior division motor fibers are destined for reinnervation of extensor targets in the contralateral paretic extremity.

When the upper plexus roots (C5 and C6) are avulsed from the spinal cord, but C7 root is preserved, reconstruction of shoulder and elbow function can be achieved by using the ipsilateral C7 root for higher priority targets. In cases with global BP avulsion, the contralateral C7 root is used as a motor donor.

Technique

The C7 root in the intact BP is explored to the level of its divisions. After longitudinal epineuriotomy and using intraoperative electrical stimulation, each bundle within each division of the C7 is mapped [42, 43]. The intraoperative mapping of the components of each C7 division is a mandatory step. Bundles that supply wrist extensors are preserved and never sacrificed. Bundles supplying the pectoralis major in the anterior division and the latissimus dorsi and triceps muscles in the posterior division are isolated with vessel loops. The former are used as motor donors for contralateral flexors and the latter for contralateral extensors.

Extraplexus Nerve Donors

In BP root avulsion injuries, a variety of extraplexus donors are recruited to reconstruct the distal plexus components. Extraplexus donor nerves for distal target neurotization include the cervical plexus motors, the spinal accessory nerve, intercostal nerves, the phrenic nerve, or the cC7 root.

Spinal Accessory Nerve Transfer

The spinal accessory nerve (XI) is a pure motor nerve, which innervates the sternocleidomastoid and trapezius muscles. Proximity of the XI to the suprascapular nerve allows direct approximation. Among other extraplexus motor donors, the

distal XI has an advantage because it is a pure motor nerve with functional characteristics similar to those of the suprascapular nerve and the neurotization can take place directly without a graft. In order to minimize trapezius muscle denervation, the nerve is transected distally after it gives off two proximal branches. At this level, the XI contains about 1,300–1,600 myelinated nerve fibers [13].

Technique

With the patient's neck turned away from the affected side, a curvilinear neck incision is made along the posterior border of the sternocleidomastoid muscle. The XI nerve can be found as it emerges along the lateral border of the sternocleidomastoid muscle, cranial to the C4 spinal nerve. The nerve stimulator confirms its identity. The transverse cervical vessels comprise a landmark for detection of the spinal accessory nerve on the anterior surface of the trapezius muscle. After these vessels are identified, a nerve stimulator is used to identify the distal part of the XI, which can be found at a mean distance of 5.2 cm from the midpoint of the clavicle along the anterior border of the trapezius.

The suprascapular nerve can be found by palpation at the level of the suprascapular notch. After identification of the suprascapular nerve, a longitudinal epineurotomy is routinely carried out with the diamond knife to decompress it in a proximodistal fashion to the level of the scapular notch.

The terminal branches of the XI are divided deep posteromedially and moved to the supraclavicular fossa and directly coapted to the suprascapular nerve. In the adult plexopathy patient the results from suprascapular nerve neurotization are significantly better if the transfer is direct without an interposition nerve graft [13].

Intercostals Nerve Transfer

Yeoman and Seddon [45] first described intercostal nerve (ICNs) transfer for BP reconstruction. ICNs are the ventral primary rami of spinal nerves T2–T11. ICNs from T7–T11 supply the muscles and skin of the anterior abdominal wall, and theoretically carry a higher number of motor axons than the upper intercostal nerves. An ICN contains less than 1,200–1,300 myelinated fibers, of which only 40 % are motor fibers. ICNs are satisfactory donors for a variety of transfers; for neurotization of musculocutaneous nerve at least three ICNs need to be used [39].

Technique

Exposure of the ICNs is achieved by elevating the periosteum of the corresponding rib. After exposure, stimulation of the motor branches takes place and the nerve is dissected proximodistally up to the level of the costochondral junction, and posteriorly to the posterior axillary line. Once all the ICNs are prepared, they are passed through a subcutaneous tunnel to the ipsilateral axilla and coapted in an end-to-end fashion to the nerve supplying the target muscle. ICNs can not be used for neurotization of both triceps and biceps as crippling co-contraction will result in the adult which should be avoided.

Phrenic Nerve Transfer

The phrenic nerve originates from the C4 and C5 roots. The phrenic nerve has mainly been used for musculocutaneous nerve neurotization. At our center, phrenic nerve neurotization has been used when the nerve is ruptured and the distal part cannot be found. In obstetrical BP palsies the phrenic nerve is used in an end-to-side manner through a perineurial window so there is no downgrading of ipsilateral function of the diaphragm [46] (Fig. 1.5).

Phrenic nerve contains about 1,300–1,600 myelinated nerve fibers. Before the phrenic nerve is considered for transfer, diaphragm and pulmonary function must be evaluated. Moreover, the entire phrenic nerve should rarely be sacrificed in a patient who has concomitant intercostal nerve harvesting, thus harvesting phrenic motor axons should be done through an end-to-side coaptation.

Technique

Following a supraclavicular approach the phrenic nerve is easily identified, lying on the anterior surface of the anterior scalenus muscle. Under

high magnification, perineurial windows are performed with partial neurotomies. Interposition nerve grafts are brought in the operating field and these are coapted with the phrenic nerve in an end-to-side fashion.

Ulnar-to-Musculocutaneous Nerve Transfer

Oberlin et al. [41] transfer of one or more ulnar nerve fascicles that were destined for the flexor carpi ulnaris to the biceps branch of the musculocutaneous nerve. This is performed to restore elbow flexion in patients who have an irreparable upper trunk injury or avulsion, and an intact lower trunk. Careful selection of ulnar nerve fascicles using intraoperative nerve stimulation enables one to perform this transfer without a donor motor deficit. The main advantage of this technique is the rapid motor recovery time because the transfer is performed so close to the target muscle without using an interposition nerve graft.

Technique

A longitudinal 10 cm incision is performed on the anteromedial aspect of the arm, starting 10 cm caudal to the acromion. The musculocutaneous nerve is identified between the biceps and the coracobrachialis muscles, followed distally to identify the nerve to the biceps. The ulnar nerve is approached at the same level and is identified by means of electrical stimulation.

The branches to the biceps are traced proximally where they usually coalesce into a single motor branch within the parent musculocutaneous nerve, and then transected. The distal part of the branch to the biceps is then rotated medially toward the previously dissected ulnar nerve. The intraoperative mapping of the components of the ulnar nerve is a mandatory step. Bundles supplying the flexor carpi ulnaris are isolated with vessel loops. These are used as motor donors for the musculocutaneous neurotization.

The chosen fascicles are separated from the rest of the ulnar nerve over a distance of 2 cm and are divided distally. The fascicles are then turned laterally and superiorly and are sutured to the nerve to the biceps under an operating microscope.

Rehabilitation

It is advisable that a nerve repair, a nerve reconstruction by interposition nerve grafts or nerve transfers are protected by immobilization, which lasts up to 6 weeks depending on the location of the nerve injury and the type of the nerve repair that was performed. Immediately, after completion of the nerve repair, a custom-made brace is applied to the patient. This brace keeps the arm abducted 45° in anterior flexion and with the elbow flexed (Fig. 1.13). The brace is removed after 6 weeks, and then a sling is applied on the patient's operated extremity for 4 weeks. This custom-made brace is applied for either brachial plexus reconstruction or

Fig. 1.13 Photo of Patient with brace (arm in anterior flexion and elbow flexed). Example of a custom made brace, applied to the patient after the nerve reconstruction

nerve repairs to the arm or forearm. In cases of digital nerve reconstruction a hand splint in the position of function (20° degrees of wrist extension, metacarpophalangeal (MP) joints at 90° degrees and intephalangeal (IP) joints in extension) is applied for 6 weeks in order to immobilize the fingers and thus preserve the nerve coaptations.

After immobilization, rehabilitation is initiated to achieve full passive and active range of motion. The rehabilitation goals in the early postoperative period are to gain full passive range of motion and to avert joint stiffness. Physical therapy with passive range of motion is started with the removal of the brace. Local application of ultrasound and massage and slow pulse stimulation are initiated at 6 weeks.

The slow pulse stimulation will be ongoing for at least a period of 2 years in cases of BP reconstruction (Fig. 1.14) or a shorter period after isolated peripheral nerve repair. The elongation of the outgrowing axons is followed by the advancing Tinel's sign, which is recorded in each follow-up visit.

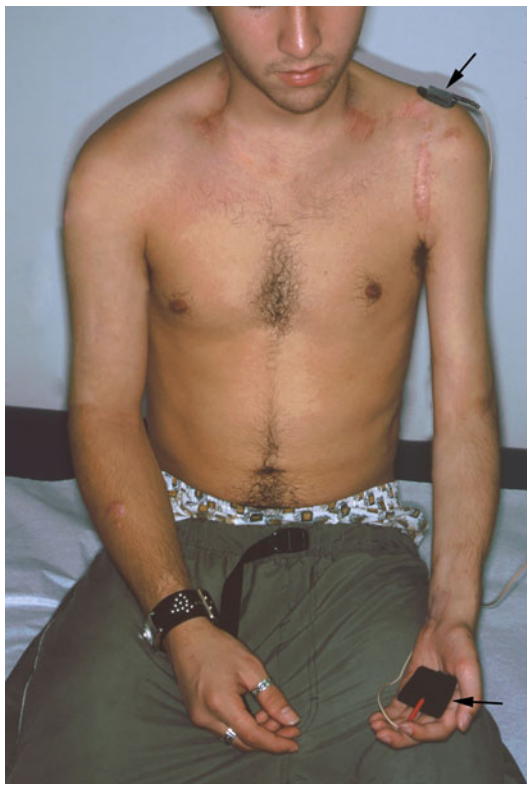

Fig. 1.14 Photo of a Patient fitted with a slow pulse stimulator. Example of a patient undergoing slow pulse stimulation. Note one "pad" is placed on the shoulder and the second on the palm (*arrows*)

Later-stage rehabilitation is focused on motor and/or sensory re-education. An effective relearning process is probably highly influenced by the motivation and compliance of the individual patient. In addition, time is spent to counsel the patient to return to his or hers previous occupation in a part-time basis or back to school during the lengthy period of nerve regeneration and functional restoration.

Outcomes

The interpretation of results of peripheral nerve and BP reconstruction has always been difficult. This is due to several reasons, including the lack of standardization and staging owing to varying degrees of nerve injury which sometimes may involve multiple levels and the lack of consensus as to the best reconstructive approach in patients with middle and high level injuries.

Several factors, such as the patient's age, the etiology and level of the lesion, associated injuries, denervation time, the length of the nerve defect, the type of repair and the surgeon's experience can influence the prognosis following nerve repair. There is no evidence which correlates smoking history with nerve recovery. Application of the principles of nerve repair (magnification, minimal tension, meticulous atraumatic technique, and experienced surgeon) can enhance the chances for a successful result.

The type of nerve repair depends on the nature of the lesion. The use of intraoperative CAPs as an adjunct in the surgical reconstruction of nerve lesions is useful in determining if there are any conducting fascicles in lesions in continuity [20, 21].

As far as BP reconstruction is concerned, overall results from a clinical series of 204 operated cases by the senior author (JKT), including 112 cases with multiple avulsions, demonstrated that intraplexus donors consistently yielded the strongest contractile force, regardless of the

muscle target [39]. In this series [39], good or excellent results were obtained in 75 % of the suprascapular nerve reconstructions, 40 % of the deltoid reconstructions and 48 % of biceps restorations. Sedel [47] suggested that even when only two roots are available for reconstruction, a good functional outcome can be expected.

The results obtained by neurotizations using unavulsed C5 and C6 roots are far superior to those achieved when utilizing extraplexus donors like the accessory or intercostal nerves. Allieu et al. [48] reported a 66 % success rate for restoring elbow flexion following neurotization by intraplexus donors (C5 or C6).

Oberlin et al. [41] described the transfer of the branch to the flexor carpi ulnaris to the motor branch of the biceps muscle without a donor motor deficit. His series using this technique showed 85 % good results of M3 or better biceps strength. Mackinnon et al. [49] reported M4 or better strength of the elbow in 6 patients who had direct transfers of motor fascicles from both the ulnar and median nerves to biceps and brachialis, respectively.

The medial pectoral nerve can also be transferred to the musculocutaneous or the axillary nerves [50]. Functional recovery for the biceps has been reported in 80–85 % of cases, and the first evidence of reinnervation occurs between 6 and 8 months [51]. The nerve to the long head of triceps can be used for deltoid muscle restoration [52, 53]. The nerve of the long head of the triceps is synergistic to the target muscle; it is a pure motor nerve with many axons and a size that matches the axillary nerve. Leechavengvongs et al. [52] reported M4 recovery was achieved in 100 % for shoulder abduction and 85 % for external rotation after nerve to long head of triceps transfer for deltoid neurotization.

Selective C7 root transfer is a reasonable donor for multiple target neurotization because it can be coated with two to four cross-chest nerve grafts [43]. The senior author (JKT) introduced the selective cC7 technique for multiple target neurotizations. Moreover, this technique can provide motor fiber for future muscle transplantation because other donors, such as intercostals, are usually consumed for shoulder and elbow reconstruction. The postoperative morbidity of the donor limb after selective cC7 technique is limited.

In a series of 56 adult patients with severe BP injuries in whom the selective cC7 technique was utilized [42, 43], 71 % of the patients experienced numbness in the median nerve area which by 6 months was indiscernible. Motor deficit was not observed. Moreover, motor recovery reached a level of M3+ or greater in 20 % of cases for deltoid, 52 % for biceps, 24 % for triceps, 34 % for wrist and finger flexors, and 20 % for wrist and finger extensors. In addition, sensory recovery of S2 or greater was achieved in 76 % of patients [42, 43].

On the other hand, Gu et al. [54], who utilized the entire cC7, reported a series of 32 patients in whom cC7 transfer was directed to musculocutaneous, median and radial nerves. Functional recovery reached M3 or greater in 80 % of patients for the biceps, in 66 % for the wrist and finger extensors, and in 50 %% for finger flexors, and S3 sensory return or greater in 12 patients (85.7 %) after median nerve neurotization [54].

It appears that some extraplexus donors give consistently superior results when used with specific targets [55]. Songcharoen et al. [56] described 80 % motor recovery ($M \geq 3$), obtaining 60° of shoulder abduction and 45° of shoulder flexion in the transfer of 577 spinal accessory nerves to suprascapular nerve. At our center, the distal accessory nerve is routinely used to reconstruct the suprascapular nerve either by direct end-to-end coaptation or by interposition nerve grafting [13]. Outcomes were good or excellent in 79 % of the patients for the supraspinatus muscle and in 55 % for the infraspinatus muscle [13].

ICNs continue to be a standard approach in the reconstruction of severe plexus lesions, especially avulsions [55]. The most common recipient nerves are the musculocutaneous and/or branches of the posterior cord. The literature reports that 65–72 % of patients obtain M3 or greater biceps recovery rates following intercostal to musculocutaneous nerve transfers [56, 57]. At our center, a total of 718 intercostal nerves were used to neurotize different targets in adult post-traumatic patients. Lower intercostal nerves (T7, T8, T9, and T10), yielded better results in

our series than upper intercostals (T3, T4, T5, and T6) and for this reason are mostly used for musculocutaneous, triceps, and axillary nerve neurotization. T4 and T5 intercostals are used more often for neurotization of the thoracodorsal and long thoracic nerves.

As far as peripheral nerve reconstruction of the upper extremity, alternative methods of reconstruction must be considered in nerve injuries with significant nerve gaps or tension, which include nerve grafting, nerve transfers and end-to-side nerve repair. Autologous nerve grafts have proven to be a popular and reliable method for the reconstruction of peripheral nerve defects [58]. Most often, the sural nerve is used as a donor graft for peripheral nerve reconstruction.

Time from initial injury to nerve grafting is often a determinant of functional outcome [59]. Vascularized nerve grafts are a valuable tool for certain indications; scarred recipient site or poor vascularity of the whole area where the nerve is to be repaired or when long defects need to be bridged.

Injuries to the ulnar nerve are the most frequent, occurring either in isolation or in association with the median nerve [60]. Kim et al. [61] reported the largest series of ulnar nerve lesions in 2003 and stated that surgical results were generally better for lesions in continuity with positive compound action potential recordings than for discontinuous lesions. Among 181 patients, favorable results were seen in 92 % of patients who underwent neurolysis, 72 % of patients with suture repair (primary and secondary), and 67 % of patients who received graft repair.

The senior author (JKT) reported her experience with ulnar nerve reconstruction in a series of 44 patients [62]. According to this, good and excellent motor results were seen in 92 % of patients who underwent neurolysis, 60 % of patients who received secondary suture repair and in 63 % of patients with graft repair.

The radial nerve is the most frequently injured nerve in the upper extremity especially in patients with multiple injuries [63]. Shergill et al. [64] and Kim et al. [65] reported the largest series of radial nerve lesions. Shergill et al. [64], reviewed 260 patients with radial nerve injuries and reported that 30 % had good results, 28 % fair and 42 % of the repairs had failed. Kim et al. [65] reported a series of 260 RN injuries in 2001. Among 180 patients, favorable results were observed in 91 % of patients who underwent primary suture repair, in 83 % of patients who underwent secondary suture repair, in 80 % of patients who received graft repair, and in 98 % of patients that had neurolysis. Our Center reported a series of 35 patients with various radial nerve lesions in 2011 [15]. Good and excellent results were seen in 100 % of patients who underwent neurolysis, in 88.88 % of patients who received suture repair, and in 57.14 % of patients with graft repair.

The use of end-to-side repair in the clinical setting for motor recovery remains controversial [14]. Currently, motor reconstruction in the absence of available proximal nerve is best handled by nerve transfers [66]. Motor neuron regeneration through end-to-side repairs is optimized by deliberate injury of donor nerve axons.

Complications of Treatment

Any kind of complication that occurs after major surgery can also occur after nerve reconstruction. Moreover, there are complications related to the type of nerve repair, which may include:

In an end-to-end neurrorhaphy the most common complications are: (1) Fibrosis in the repair site from sutures placement or inadequate recipient bed, and (2) Misdirection of the nerve fibers due to improper alignment of the nerve stumps.

As far as nerve grafting is concerned, the most common complications are: (1) Sensory loss and scarring in the donor site; (2) Neuroma formation in the proximal stump of the donor-nerve, and (3) Failure of the graft to survive if the repair took place in a vascularly compromised bed.

In nerve transfers complications may include: (1) Loss of function from donor nerve site and (2) Donor muscle atrophy. In end-to-side neurorrhaphy complications include: (1) Donor axonal injury and (2) Donor muscle atrophy.

Conclusions

Advances in the field of peripheral nerve surgery have increased our understanding of the complex molecular and cellular events surrounding nerve injury and repair. There are several factors that influence recovery following a nerve injury: time elapsed, patient age, mechanism of injury, proximity of the lesion to distal targets, and associated soft tissue or vascular injuries. All these factors must be carefully considered in order to optimize the operative approach used in each patient. Prompt repair of nerve injuries leads to improved outcomes by allowing for earlier distal motor end plate and sensory receptor reinnervation.

The ultimate goal of any peripheral nerve reconstruction is the restoration of function as promptly and completely as possible, while minimizing comorbidities. If end-to-end repair is not possible, several options for repair include interpositional nerve grafting, nerve transfers and end-to-side neurorrhaphy. Selection of each technique depends on the surgeon's experience and individual nerve injury characteristics.

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