World J. Surg. 25, 1049–1061, 2001
DOI: 10.1007/s00268-001-0058-8

WORLD
Journal of
SURGERY

Brachial Plexus Root Avulsions

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Published Online: July 9, 2001

Abstract. The majority of adult brachial plexus palsies are posttraumatic injuries caused by high-energy forces, usually involving motor vehicles. In infants, brachial plexus palsies commonly represent obstetrical injuries following excessive traction on the plexus during complex or difficult delivery. Most adult injuries, and occasionally those in infants, represent brachial plexus root avulsion injuries that carry serious ramifications from the standpoint of permanent disability of a paralyzed extremity, prolonged recuperation, and significant socioeconomic impact. Modern-day management of root avulsions should focus on early, aggressive microsurgical reconstruction of the brachial plexus, combining various neurotizations with intraplexus and extraplexus ipsilateral and contralateral nerve donors, utilization of vascularized nerve grafts, and finally the use of free vascularized and neurotized muscles. When these multistage microsurgical management techniques are applied early (with complete avulsions) they may often result in significant return of neurologic function, especially in young patients. Amputation should be looked upon as an option only when these newer microsurgery techniques have failed.

The number of severe brachial plexus injuries requiring medical management has increased over the past several years, largely in part to improved prehospital emergency medical service capabilities, and advanced life support techniques. In spite of increased experience in the management of these devastating brachial plexus injuries, there remains considerable debate as to the optimum management, especially with complete nerve root avulsions.

The major problem with avulsions is the lack of adequate proximal intraplexus donors (roots) in continuity with the spinal cord. Anatomical restoration of the brachial plexus is often impossible. In turn, the extremely difficult challenge for any reconstructive microsurgeon is the ability to identify and sacrifice less important neuromuscular sensory functions in order to direct and use motor fibers for neurotization to achieve basic functions to the flail upper extremity.

Neurotization techniques were introduced early in the twentieth century, giving hope for the restoration of severe brachial plexus injuries [1, 2]. This initial surgical enthusiasm, unfortunately, eventually gave way to a more pessimistic attitude of "wait and see," as almost all of these earlier surgical techniques were unsuccessful in restoring neurologic function. A nonoperative approach was eventually advocated for all brachial plexus injuries, except for the occasional need to explore the brachial plexus in order to accurately determine prognosis [3–9]. About the only feasible alternative available for a flail and anesthetic arm was to amputate through the upper arm, fuse the shoulder, and fit the patient with a prosthesis [10], or use specialized arm splints [11].

With the advent of newer diagnostic technologies such as cervical myelography [12], electromyography [13], recording of nerve action potentials [14], and the histamine test [15], clinical ability to exactly determine the site and extent of brachial plexus injuries was dramatically improved and enhanced prognostication.

Introduction of microsurgical techniques [16–18] in peripheral nerve surgery and the establishment of the principle of tension free repair [19, 20] brought several new approaches to brachial plexus reconstruction, especially when dealing with supraclavicular lesions with multiple avulsions. A variety of extraplexus motor and sensory donors has been advocated to neurotize selected muscles in order to achieve essential function in the shoulder, elbow, and hand. Yeoman and Seddon [21] introduced neurotization of the musculocutaneous nerve with intercostal nerve transfer. In addition, use of branches of the ipsilateral cervical plexus [22], contralateral lateral pectoral nerve [23], accessory nerve [24], hypoglossal nerve [25, 26], phrenic nerve and contralateral C7 [27, 28], selective contralateral C7 [29], and selective ulnar nerve to musculocutaneous [30] has been championed by different researchers.

Vascular nerve grafts were added to the armamentarium of managing brachial plexus avulsion injuries when the first free vascularized nerve graft (superficial radial nerve) was performed by Taylor and Ham [31] in a case of median nerve paralysis. Daniel and Terzis described application of the superior ulnar collateral artery in 1975 [32], and in 1981 Terzis utilized the same vascular pedicle to transfer the entire ulnar nerve as a free microvascular transfer [33]. This allowed for the successful use of a trunk graft as a massive carrier of regenerating axons, without sacrifice of a major artery in the paralyzed extremity. The successful free vascularized transfer of the ipsilateral ulnar nerve in cases

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of lower root avulsion dramatically improved the prognosis of devastating brachial plexus injuries.

Restoration of functional finger flexion and extension has remained largely unobtainable following avulsion injuries. The prolonged time required for nerve regeneration results in muscle atrophy and subsequent fibrosis, leaving the muscles inadequate to generate the force required to move the fingers. Further advances in microsurgery have brought about the era of free functional muscle transfers in the management of brachial plexus paralysis [34–36]. Palliative procedures, e.g., muscle transpositions or tendon transfers [37–39], also enhance the functionality of the paretic arm. The experimental work of Carlstedt [40] demonstrated reinnervation through avulsed roots implanted in the spinal cord. Although muscle function was restored following replantations for root avulsions, functional outcome was compromised due to severe cocontraction. Further experimental work is needed before this approach can have any meaningful clinical application.

Current Management

Establishment of Diagnosis

Any precise preoperative assessment should include an explicit history as to the mechanism of injury, the patient's overall physiological status, comprehensive physical examination, and numerous paraclinical supporting studies, including radiologic and electrophysiological technologies. Such preoperative data are essential to arrive at a definitive diagnosis and eventually to establish a reasonable reconstructive plan and prognosis.

Root avulsions should be ruled out in cases of: (1) high-velocity impact to the brachial plexus region; (2) concomitant fractures and/or dislocations about the shoulder; (3) upper extremity vascular trauma; (4) presence of a Horner sign; (5) coexistent palsy of the phrenic and/or accessory nerves; (6) severe pain associated with a flail and anesthetic arm; and (7) the presence of pseudomeningocele(s) on cervical myelography.

The combination of a cervical myelogram and computerized tomography (CT) post myelogram is considered the best modality for examining the cervical ventral and dorsal rootlets, with a low rate (3.5%) of false negative results [41]. Conventional magnetic resonance imaging (MRI) is preferred for revealing the cervical roots beyond the foramina, and especially for defining space-occupying lesions such as tumors in the brachial plexus. The overall accuracy in detecting damaged nerve roots or root sleeves has been improved with the technique of magnetic resonance myelography, which surpasses conventional myelography and is similar in accuracy to that of CT post myelography [42].

Electrodiagnostic evaluation should include electromyography, nerve conduction velocities, sensory action potentials, and percutaneous lamina stimulation tests [43]. In the latter, tiny volleys of electrical stimulation are applied on each exiting root to determine if the patient perceives the area of the dermatome subserved by this root. A positive response would be strong evidence against avulsion. The presence of sensory nerve action potentials (SNAP) and normal sensory conduction velocities invariably imply root avulsion in peripheral nerves innervating a flail and anesthetic extremity. The final conclusive diagnosis of root avulsion, however, is usually made intraoperatively.

Timing of Reconstruction

The optimal timing for reconstruction in the treatment of closed traction injuries has long been controversial. An attitude of "wait and see" essentially has no place in modern-day management of these injuries, since there is minimal or no benefit from late nerve reconstruction when performed longer than 2 years after denervation.

Magalon et al. [44] and Brunelli [45] promote emergency repair of lesions associated with vascular trauma, while Alnot [46] prefers exploration of the plexus during vascular repair and reconstruction as a secondary procedure. Sedel [47] supports the results obtained from repairs done up to 9 months following injury as being better than those achieved after a longer delay in reconstruction. It is our opinion that aggressive early reconstruction within 6 weeks to 3 months post injury provides the most optimal results.

Strategy of Nerve Reconstruction

Patients with root avulsions should be extensively informed as to what is implied by a multistaged reconstruction. They should be offered a realistic expectation with the goal of partial return of function and use of the paralyzed extremity as an accessory limb during daily activities. The overall goal of reconstruction should be directed toward regaining important functions of the upper extremity (i.e., shoulder stability, elbow flexion, elbow extension, protective sensation in the hand, and, if feasible, hand reanimation).

Exploration of the entire supraclavicular brachial plexus is usually required to identify and assess the degree of damage to the cervical roots. Cross-sections of the roots are sent to the surgical pathology lab for immediate (frozen section) microscopic assessment as to the presence of axons, ganglion cells, and/or excessive scar tissue. When ganglion cells are present, the root should be considered avulsed and therefore unusable as a donor for neurotization. Additional histochemical analysis of the roots with carbonic anhydrase [48] and cholinesterase [49] is available in specialized centers, and may provide further information regarding the sensorimotor distribution of a nerve biopsy site.

Somatosensory evoked potentials (SEP) record the response of the opposite cerebral brain hemisphere to electrical stimuli at the root level by utilizing superficial recording electrodes and have been reported to be a reliable method in ruling out avulsion [50]. Motor evoked potentials (MEP) have been employed to diagnose avulsion of anterior (motor fiber) rootlets [51]. This technology records action potentials at the root level after transcranial electrical stimulation of the brain. A positive response implies continuity and thereby excludes avulsion of that specific cervical root.

An intraoperative assessment of the severity of a brachial plexus lesion was developed by the senior author (JKT), the Terzis Brachial Plexus Severity Score (TBPSS). Each root is graded as follows: 0 = Avulsion, 1 = Avulsion/Rupture, 2 = Rupture, 3 = Rupture/Traction, 4 = Traction, and 5 = Normal. A normal (TBPSS) would equal 25. The lower the severity injury score the worse the injury and prognosis, as well as decreased availability of intraplexus donors for neurotization. The authors' preferred reconstruction for various combinations of root avulsion are as follows:

One or Two Root Avulsions. Prognosis is best when avulsion affects the upper plexus, because in these cases the hand is spared. If C5 and/or C6 are avulsed, selective regions of the posterior division of C7 are guided to the posterior cord and parts from the anterior division of C7 are guided to the lateral cord. In cases of lower root avulsion in infants the C8 and T1 can be neurotized from C5, C6, or C7; however, this is not feasible in adults because of the long distances involved for neurotization of the hand and the fact that recovery of small muscles of the hand is virtually impossible.

CASE 1: TWO ROOT AVULSION RECONSTRUCTION. A 22-year-old male sustained a right brachial plexus injury following a high-speed (65mph) motor vehicle collision (Fig. 1a). Five months later, exploration of the brachial plexus revealed rupture of C5 and rupture/avulsion of C6 with formation of a large neuroma extending beyond the clavicle, avulsion of the C7 root, while the C8 and T1 roots sustained rupture/traction (Fig. 1b). Reconstruction included: (1) neurotization of the suprascapular nerve with the terminal branch of the accessory nerve; (2) neurotization of the lateral cord (musculocutaneous and median) from C5 and of the posterior cord (axillary) from C5 and C6 using sural nerve grafts; (3) neurotization of the lateral pectoral nerve from C6; and (4) microneurolysis of C8 and T1, along with partial nerve grafting of the lower trunk (Fig. 1c). In addition to this initial procedure the patient also underwent free latissimus dorsi transfer to enhance elbow flexion. The muscle was neurotized directly with three intercostals (T6, 7, 8). A rotational osteotomy of the humerus facilitated external rotation of the arm, while a free gracilis muscle transfer was used to enhance finger extension and a tendon transfer of the flexor carpi ulnaris to the extensor carpi radialis brevis allowed wrist extension. Figures 1d to 1g depict the patients function at follow-up 6 years postreconstruction. Figures 1h and 1i show the pre- and postoperative brachial plexus charts.

Three or Four Root Avulsions. Usually the lower roots are involved (C7, C8, T1), but the force of this injury may affect the upper roots as well. If only C5 and C6 are available, the suprascapular nerve is neurotized from the terminal branch of the accessory nerve, while the ipsilateral ulnar nerve is utilized as a vascularized nerve graft to connect C5 and C6 with the musculocutaneous, median and radial nerves. The ulnar nerve, based on the superior ulnar collateral vessels, can be connected to two or three targets at the same time with the donor root(s) by employing the "loop" technique as introduced by Terzis in 1981 [33]. Through perineurial windows the fascicles are divided, coapted to the root(s) and the distal targets, while maintaining the nerve's epineurial blood supply. Regeneration through this vascularized trunk graft is generally faster than conventional nerve grafts (7–12 cm a month) [33].

CASE 2: THREE ROOT AVULSION RECONSTRUCTION. A 15-year-old black male sustained a left brachial plexus injury and concominant fracture of the left clavicle and disruption of the left subclavian artery following a motor vehicle collision. Immediate repair of the artery was performed with a reversed saphenous vein graft (Fig. 2a).[12] Three months later exploration of the brachial plexus revealed C5 and C6 ruptures and C7, C8, and T1 avulsions (Fig. 2b). Reconstruction of the plexus was accomplished by: (1) neurotization of the axillary and lateral pectoral nerves from C6 via sural nerve grafts; (2) neurotization of the musculocutaneous, median, and radial nerves from C5 and C6 through a vascularized ulnar nerve graft, utilizing the "loop" technique; and (3) direct neurotization of the suprascapular nerve with the accessory (Fig. 2c). Two years later a free gracilis was employed for finger extension and directly neurotized with two intercostals. Figures 2d to 2h illustrate the patient as seen 4 years following the nerve reconstruction. Figures 2i and 2j depict the preoperative and postoperative brachial plexus grading charts. Of note is the fact that because of the patient's history of juvenile delinquency, he had minimal, if any, compliance in rehabilitation and postoperative physical therapy.

CASE 3: FOUR ROOT AVULSION RECONSTRUCTION. When only C5 is available and the brachial plexus is prefixed, a similar strategy of reconstruction is followed. In this case the C5 root was large enough to accommodate three targets (musculocutaneous, median, and radial nerves). This 32-year-old male sustained a left brachial plexus injury after a high-speed motorcycle collision. The patient's initial presentation was that of a flail and anesthetic upper extremity with intolerable pain (Fig. 3a). Six months post injury a cervical laminectomy and a dorsal root entry zones (DREZ) procedure of the left side of the spinal cord was performed prior to exploration of the brachial plexus. At exploration of the brachial plexus, C5 was found ruptured and the rest of the roots were all avulsed (Fig. 3b). Reconstruction included neurotization of the musculocutaneous and median nerves, as well as the posterior cord from C5 via a vascularized ulnar nerve graft, again utilizing the "loop" technique (Fig. 3c). The patient also underwent secondary procedures including wrist fusion, free gracilis transfer for finger extension, and free latissimus dorsi transfer for posterior deltoid and triceps substitution. Figures 3d to 3i show the patient as seen in follow-up 3 and 6 years post reconstruction. Figures 3j and 3k depict the pre- and postoperative brachial plexus charts.

When the brachial plexus is postfixed and the C5 root tiny, the musculocutaneous nerve is connected with conventional nerve grafts, and the ulnar nerve reserved for connecting the contralateral C7 and the ipsilateral median nerve as a second stage procedure. The posterior cord elements including the axillary nerve, nerve to the triceps, and radial nerve are neurotized by extraplexus motors including the ipsilateral intercostals, partial phrenic, and cervical plexus motor donors.

Global Avulsion. The lack of intraplexus donors in these devastating injuries necessitates consideration of extraplexus ipsilateral or contralateral donors to serve as axonal pools. Because of the extent of injury sustained, one should be cautious in employing ipsilateral nerves because of their own possibility of injury. Preferred neurotizations are: (1) accessory to suprascapular directly; (2) intercostals used to neurotize either anterior or posterior targets, but not both, in order to avoid cocontraction; and (3) the partial phrenic, the cervical plexus motor branches, the partial hypoglossal, and the anterior and posterior divisions of the contralateral C7 may all be used to neurotize as many targets as possible. The senior author (JKT) has employed the phrenic and the hypoglossal through end-to-side neurorraphies, with partial neurectomy of the donor nerve, so that the original targets are not

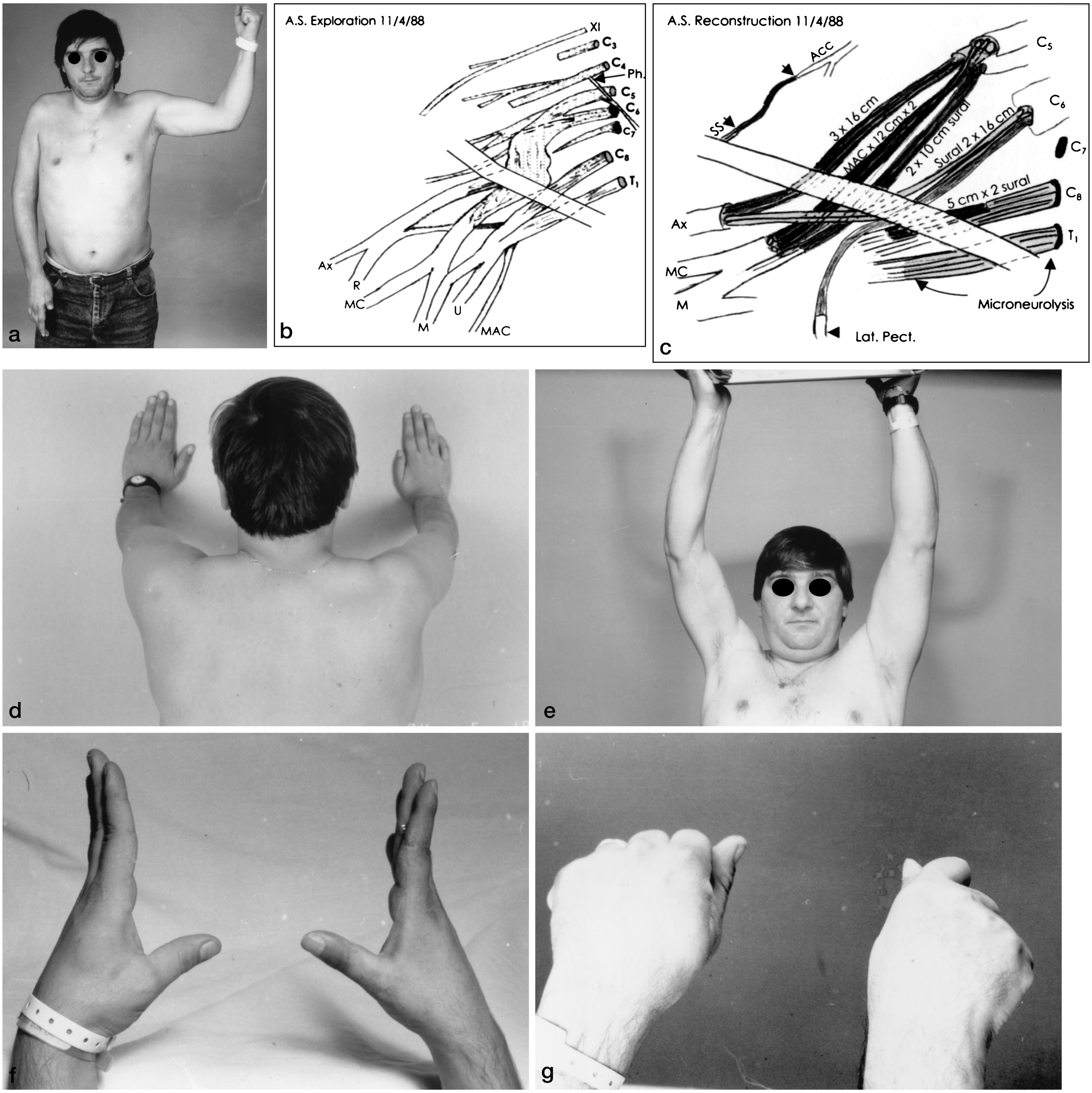
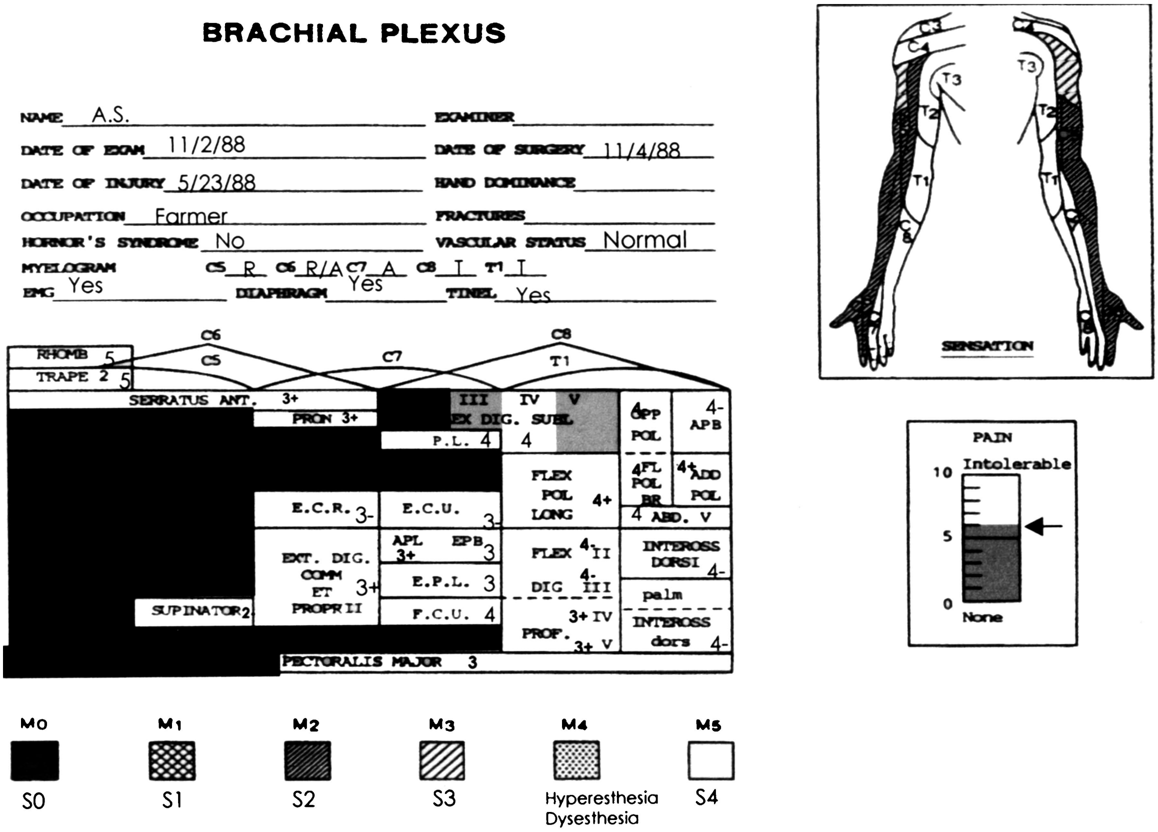


Fig. 1. a. Preoperative. Note the paralyzed and atrophied right upper extremity. **b.** Brachial plexus exploration. **c.** Brachial plexus reconstruction. **d.** Note in the back view the bulk of the deltoid and the normal positioning of the scapula demonstrating good serratus anterior function. **e.** Excellent shoulder and elbow function. **f.** Finger extension and thumb abduction. **g.** Strong finger flexion. **h.** Preoperative plexus chart. **i.** Postoperative plexus chart.

downgraded. Sometimes in order to match the axonal number of the target to the lesser number of axons afforded by the donor, two or more donor nerves may be directed to the same critical target (i.e., musculocutaneous nerve). Whenever possible, direct coaptation to the recipient nerve is preferred. Also keep in mind that when using intercostals for neurotization, at least three intercostals will be required for reconstruction of the musculocutaneous nerve. Protective sensation may be provided to the median nerve from sensory branches of the intercostals and/or from the sensory supraclavicular nerves. Nerve grafts connected proximally with any variety of motor donors may be banked subcutaneously at the arm or elbow level for future neurotization of free muscle transfers.

Pain Management

In spite of the upper extremity being totally flail and anesthetic, it is the intolerable constant pain that usually leads the patient to



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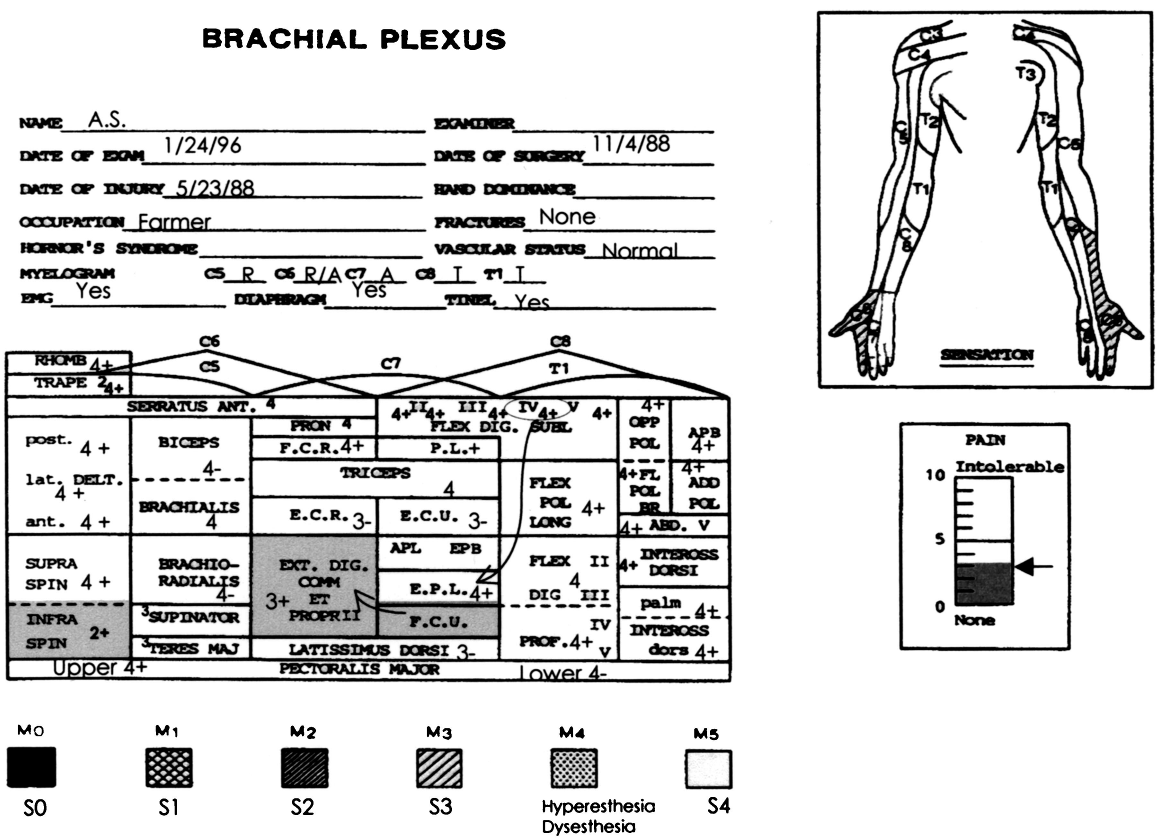

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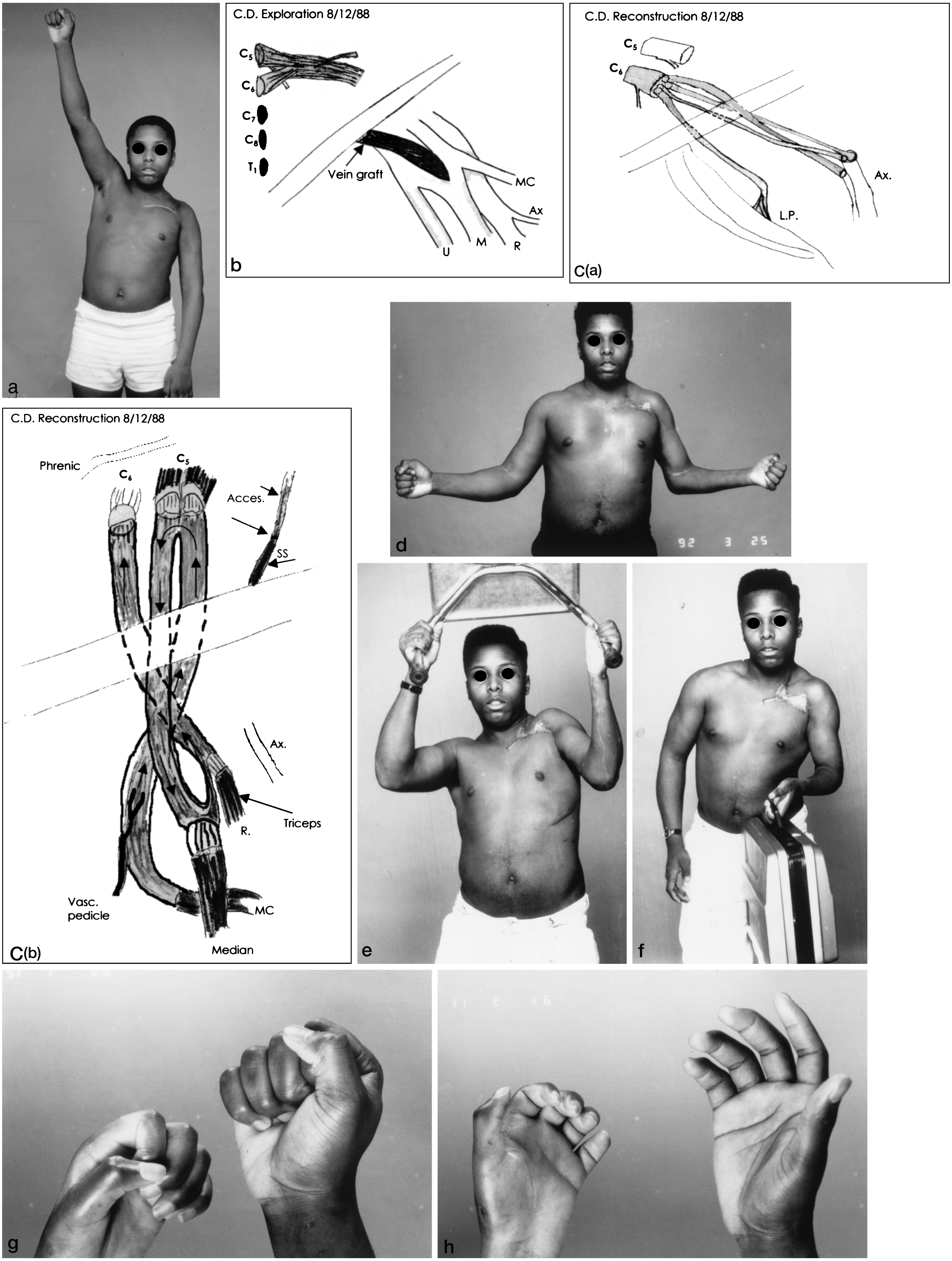


Fig. 2. a. Preoperative visit. Note the paralyzed extremity, and the scar from reconstruction of the subclavian artery. **b.** Brachial plexus exploration. **c.** Brachial plexus reconstruction. **d.** Good external rotation and biceps function. **e.** Strong elbow flexion, adequate deltoid function, stable wrist, and good grip easily allowing the patient to lift a stool. **f.** Patient lifting a suitcase. **g.** Sufficient finger flexion to provide an adequate grip. **h.** Ability to extend the fingers to the MP joint, because of the free muscle transfer, but not in the IP joints because of the intrinsic palsy. **i.** Preoperative plexus chart. **j.** Postoperative plexus chart.

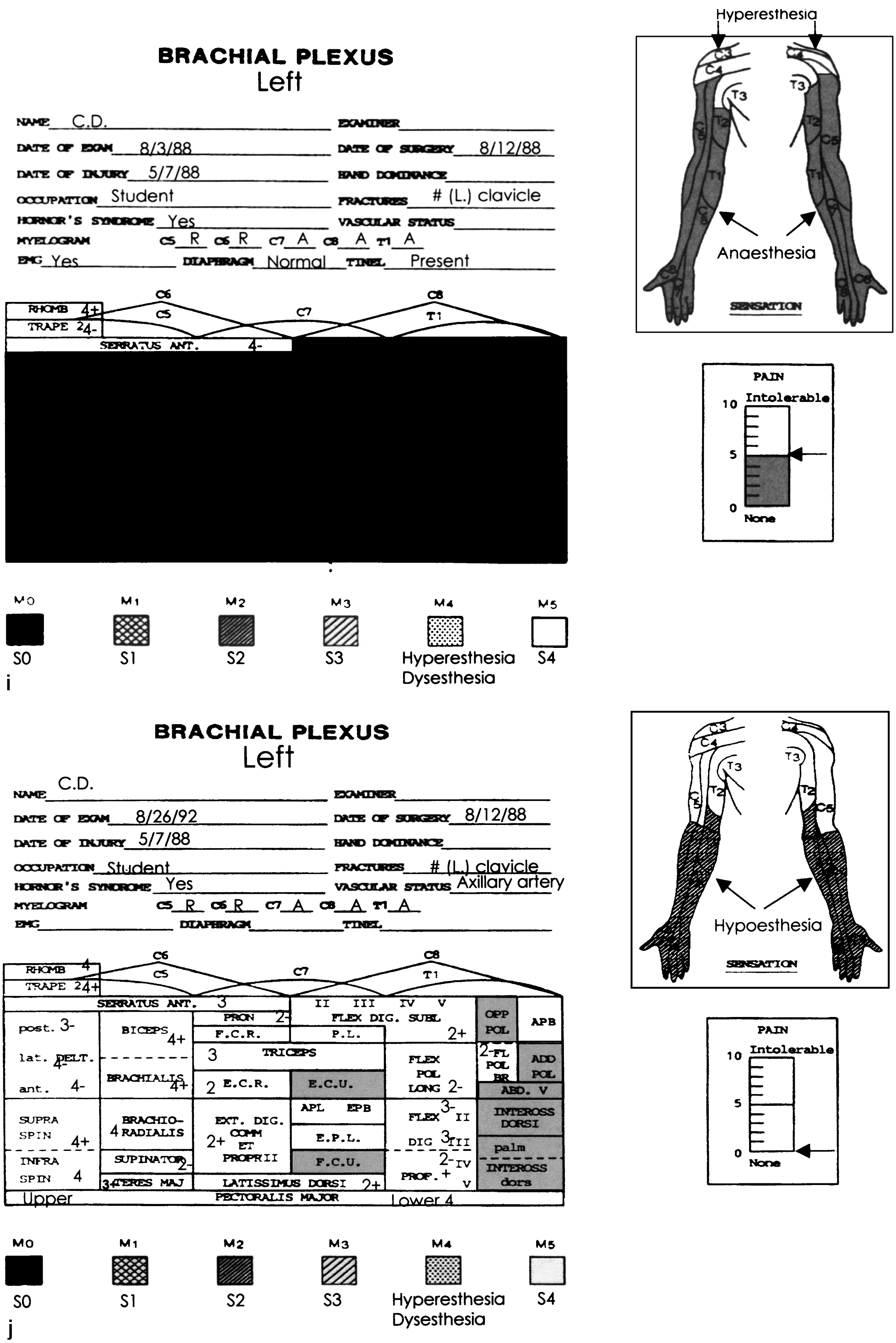


Fig. 2. Continued.

seek definitive relief through amputation. Although amputation is still practiced, control of the pain can actually be achieved by any number of more conservative methods such as analgesics and/or electrical stimulation. Should these fail, surgical intervention consisting of coagulation of the dorsal horn at the levels of the avulsed roots at the dorsal root entry zones in the spinal cord

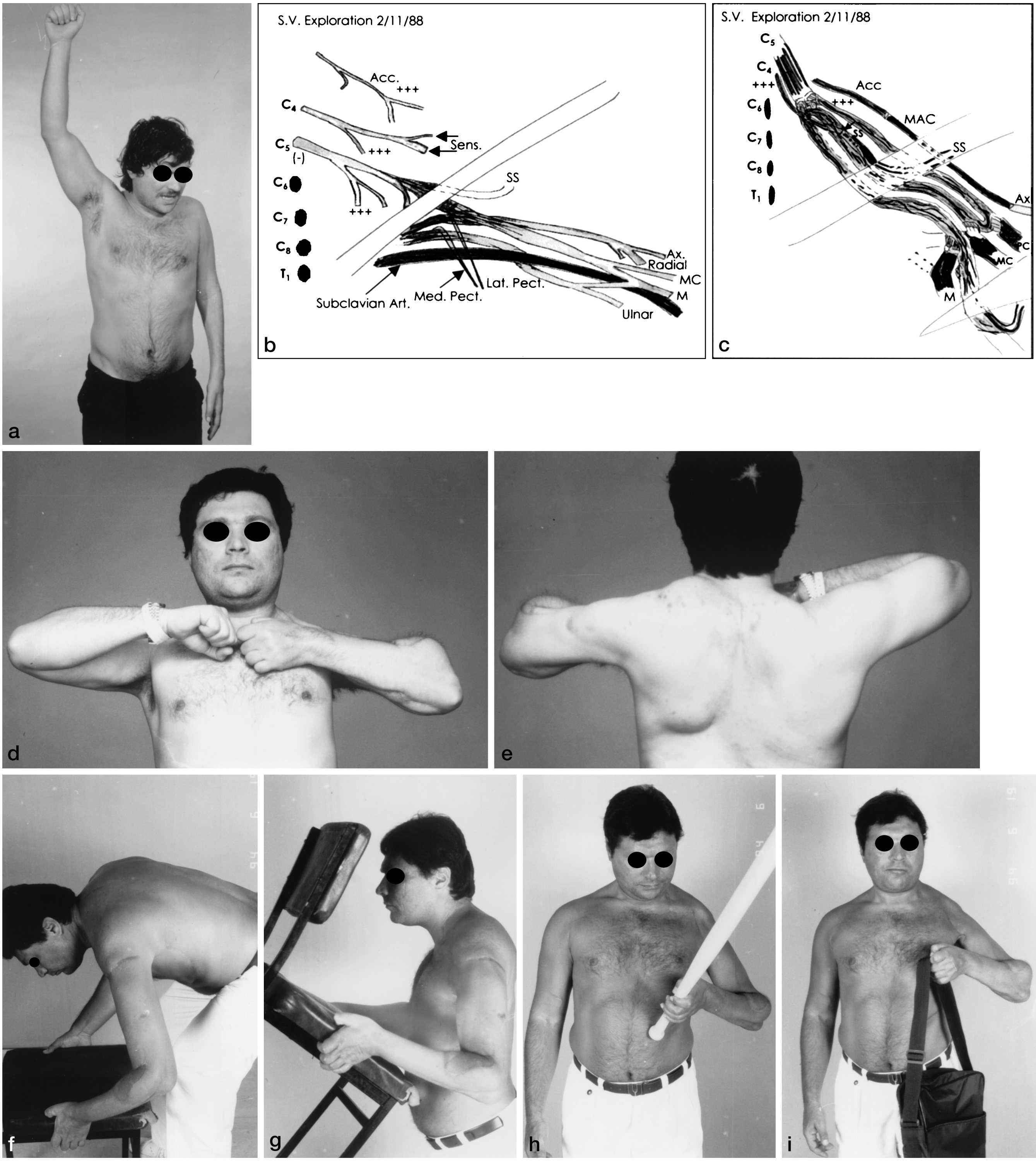
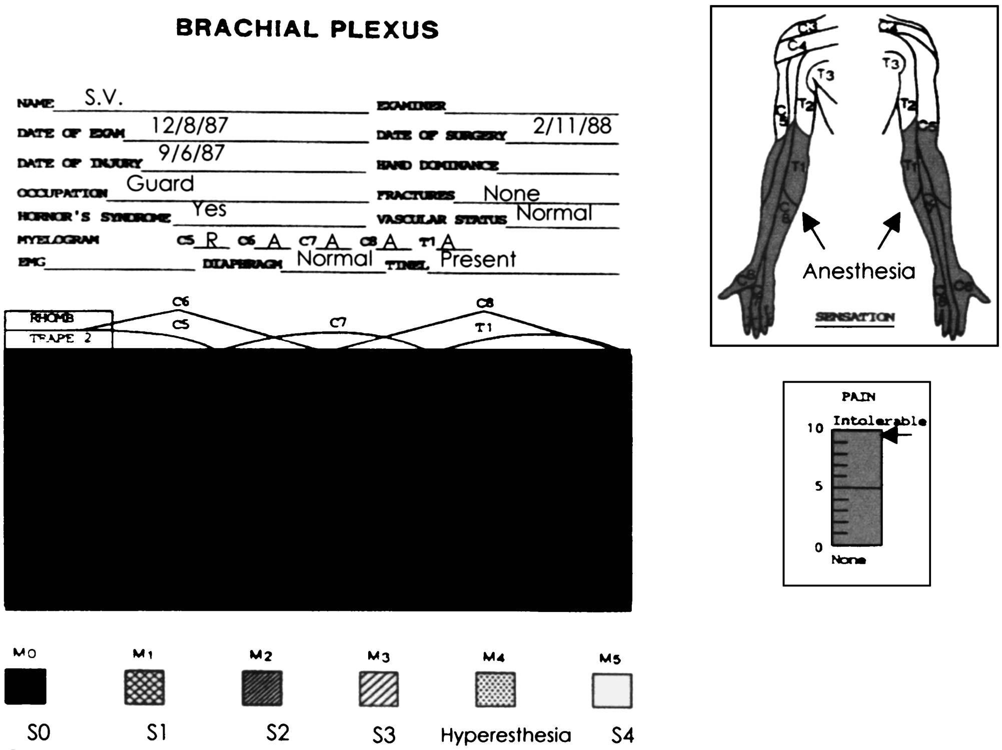


Fig. 3. a. Preoperative. A total anesthetic and paralyzed extremity with intolerable pain. **b.** Brachial plexus exploration. **c.** Brachial plexus reconstruction. **d.** Good shoulder abduction 3 years post injury. **e.** Note the functional and bulky deltoid. **f, g.** Six years following brachial plexus reconstruction. Patient easily lifts a chair, demonstrating good grip and strong elbow flexion. **h.** Satisfactory grip holding a baseball bat. **i.** Lifting a shoulder bag. **j.** Preoperative plexus chart. **k.** Postoperative plexus chart.

(DREZ) procedure as developed by Nashold [52] , is a much more attractive option. This procedure should precede any nerve reconstruction. Microsurgical restoration may also be beneficial in controlling pain.

Secondary Procedures

Procedures such as muscle transfers and wrist fusion may be required to improve final function, especially in those cases



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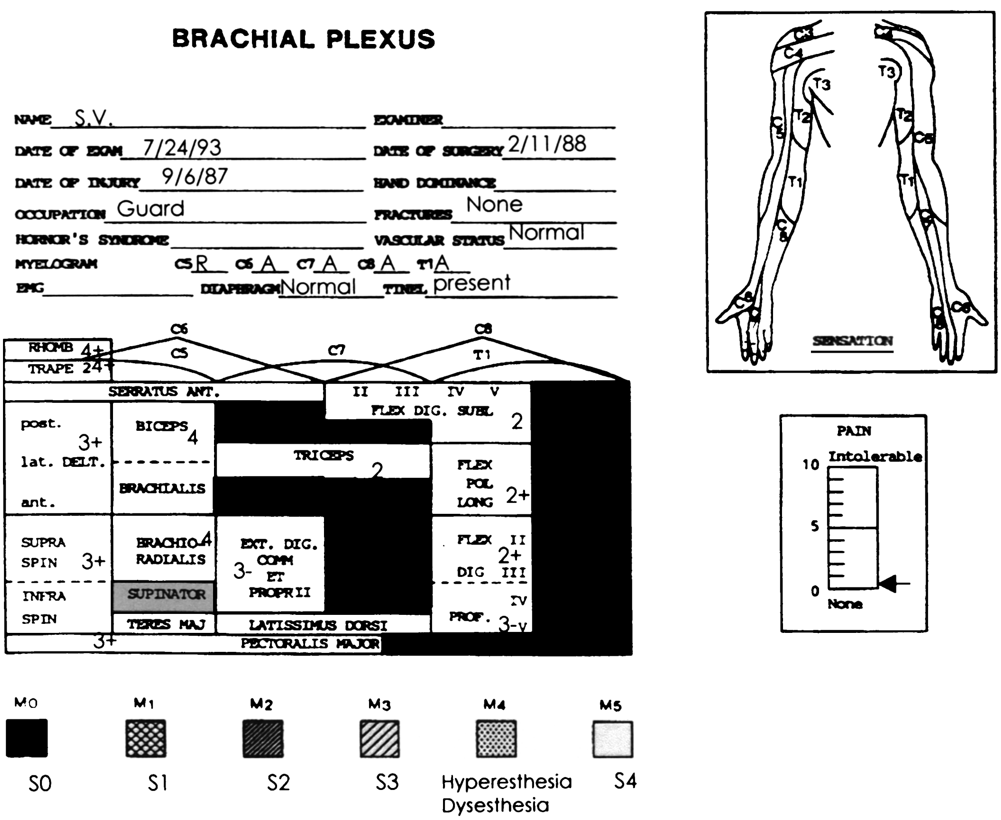

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Fig. 3. Continued.

treated late wherein the muscle targets have atrophied. The transferred free muscles are neurotized either by previously banked nerve grafts or directly from local motor donors (i.e., intercostal nerves). The most commonly restored functions are those of elbow flexion and extension, finger flexion and extension, and, in some cases, shoulder abduction and intrinsic substitution.

For shoulder and elbow reanimation, the latissimus dorsi can be used as a pedicled [53] or free muscle transfer [54]. The pectoralis major with or without pectoralis minor may be transferred as an island flap [37]. Rectus femoris transfer has been found to be helpful in elbow flexion restoration [54]. For hand reanimation, gracilis and rectus femoris may both be used [54]. In some cases, it is possible to restore two functions with one muscle transfer (i.e., elbow flexion and finger flexion or elbow extension and finger extension) [36, 55].

Discussion

The improved modern-day outcome of brachial plexus reconstruction, even with severe palsies involving root avulsions, is obviously multifactorial, but is largely due to the advent of microsurgical techniques and better understanding of the nature of brachial plexus injuries and their response to treatment. As most patients prefer preservation of the limb, even if it is partially paralyzed and even if it has only partial function, any number of microsurgical techniques should be used to maximize restoration of muscle and sensory function, thereby avoiding amputation.

Important factors in determining the prognosis of any given lesion are the age of the patient, the denervation time (meaning the time interval between the injury and reconstruction), and the severity score, to objectively grade the degree of root injury as found at the time of surgical exploration [54]. The best outcomes can be expected to occur in younger patients with short denervation times and a high severity score [54].

The outcome of reconstruction was found to be significantly superior in younger patients for the restoration of biceps, triceps, and hand reanimation. With denervation times of less than 6 months superior results were obtained in the restoration of biceps function and hand flexion, suggesting that the flexors of the upper extremity are more sensitive to prolonged denervation [54].

Gu et al [56] presented a series of avulsion injuries with good results following various nerve transfers (following the principles of tension-free repair) in young patients operated upon early. Hentz and Narakas [57] also advocated early exploration with complete palsies and suggested improved outcome in younger patients. Nagano [58] concluded that the best results in avulsion injuries were achieved in patients younger than 30 years of age and when operated upon less than 6 months after injury.

In general, most authors have reported better results in upper root palsies. The reason for this is twofold. Most important, the hand is spared, and second, the muscle targets of reconstruction are closer to the plexus. The latter also explains the improved outcome when dealing with proximal muscle targets (e.g., supraspinatus and biceps).

Whenever possible, the use of intraplexus motor donors for neurotizations is preferable. Intraplexus donors have a larger number of axons than extraplexus sites, and thereby increase the chances for successful neurotization. Overall results from our clinical series of 204 operated cases, including 112 cases with multiple avulsions, demonstrated that intraplexus donors consistently yielded the strongest contractile force, regardless of the muscle target [54].

It has been suggested that outcome is improved in the presence of proximal healthy roots [57]. The results obtained by neurotizations using unavulsed C5 and C6 roots are far superior to those achieved when utilizing extraplexus donors like the accessory nerve. Extraplexus nerve transfers should be considered second-choice alternatives [59]. Allieu et al. [60] reported a 66% success rate for restoring elbow flexion following neurotization by intraplexus donors (C5 or C6). This was superior to neurotization with intercostals or the accessory using an interposition nerve graft. Kawai et al. [61] reported that the outcome was better in 80% of avulsion injuries treated with the combined use of intraplexus and extraplexus donors. Narakas and Hentz [62] considered plexoplexal transfers as far more reliable than extraplexal, and even superior to muscle transfers in the reconstruction of shoulder abduction, elbow flexion, or wrist extension.

It appears that some extraplexus donors give consistently superior results when used with specific targets. Intercostal nerves continue to be a standard approach in the reconstruction of severe plexus lesions, especially avulsions. The most common recipient nerves are the musculocutaneous and/or branches of the posterior cord. The accessory nerve is another reliable extraplexus donor for neurotization. We have previously reported that direct neurotization of the suprascapular nerve with the accessory nerve yielded comparable results to those using intraplexus donors. Neurotization of the suprascapular nerve gave 75% good or excellent results (M3+ to M4+). Direct neurotization with intercostals was felt superior to all other extraplexus donors utilized for biceps, triceps, finger flexion, and finger extension restoration. The overall restoration of elbow flexion was 60% good to excellent and was obtained by combined neurotizations from intraplexus donors and intercostals [54].

Narakas and Hentz [62] stated that neurotization with the accessory nerve gave good results in only 35% of patients. Neurotization of the musculocutaneous with intercostals gave 60% fair to excellent results, while for the rest of the targets (median, radial, axillary, suprascapular) the results were found to be fair to excellent in 38% of patients. Various intraplexus donors achieved 50% good elbow flexion results; however, shoulder function was limited and no useful finger flexion was gained.

The Japanese school advocates use of the intercostals routinely. Nagano [63] supports the direct neurotization of the musculocutaneous with intercostals over the use of interposition nerve grafts, with resultant 70% good or excellent biceps function (muscle grading of M 3 or more). Ogino and Naito [64] consider intercostal transfers as a useful procedure in restoring elbow flexion and protective sensation of the hand. Kawai et al. [61] achieved satisfactory results in 64% of neurotizations for elbow flexion with intercostals and spinal accessory nerves following avulsion injuries.

Malessy and Thomeer [65] reported functional elbow flexion in 64% of the patients operated upon with direct intercostal transfers. They did not find substantial differences in the results obtained with accessory nerve neurotization. Waikakul et al. [66]. when comparing the results of musculocutaneous neurotization with accessory and intercostals presented 83% and 64% good to very good results respectively. However, the intercostals gave earlier electromyographic evidence of motor reinnervation, better protective sensation, and greater reduction of pain. Bentolila et al. [67] reported a successful result (M3+ or more) in 55% of the patients with respect to recovery of biceps function after transfer of the spinal accessory nerve to the musculocutaneous nerve. Songcharoen et al. [68] reported 72.5% satisfactory results (M3 or more) with neurotization of the musculocutaneous with the accessory.

Alnot [46] stated that with global avulsions, elbow flexion of M3 to M4 could be achieved in 75% of patients with neurotization of the musculocutaneous by the accessory and motor branches of the cervical plexus. Unfortunately, restoration of hand function was not commented on in this particular series. After neurotization with the accessory and phrenic to the musculocutaneous, suprascapular, and axillary, Songcharoen [69] reported good results in 75%. Neurotization with intraplexus donors gave 71% good results, while neurotization of the musculocutaneous with intercostals was less satisfactory (65% fair to good result).

Other extraplexus donors produced less rewarding results for specific targets. Cervical plexus motors and contralateral C7 gave overall inferior outcomes as related to hand reanimation [54]. A plausible explanation is that with cervical plexus motors the small number of fibers originally destined for short distances are now being forced to cover a longer distance. In the case of the contralateral C7, the length of the cross-chest nerve graft automatically imposes a necessary delay prior to target connectivity. Gu et al. [70] reported that neurotizations from the contralateral C7 by means of a vascularized ulnar nerve resulted in recovery of the biceps and finger flexors up to M3 in 60% and of the triceps up to M4 in 50%.

Reconstruction strategies for brachial plexus injuries vary widely in different reported series. With multiple root avulsions the prevailing attitude, to date, has been to reconstruct only the shoulder thereby providing stability and some motion as well as elbow flexion, without attempts to restore function of the hand. Personally, we consider restoration of hand function the highest priority whenever possible in the appropriate patient, in spite of the fact that the results of hand reanimation with neurotizations are not nearly as successful as restoration of elbow flexion. Utilizing neurotizations with intraplexus donors and intercostals, Sedel [71] reported good or excellent results in 13% of the patients at the shoulder, in 45% for elbow flexion, and in 22% for triceps. Only 16% of the patients with complete palsies had fair results for hand flexion. He concluded that outcome was better whenever at least two or more roots were available for neurotization. When only one root was available the results were generally disappointing.

Millesi [19] reported on the use of intercostals to neurotize the musculocutaneous nerve and obtained useful elbow flexion in 58.9%. Neurotization of the suprascapular and axillary with the accessory gave stability of the shoulder in 61% of the patients. In this study, results were regarded as useful if strong elbow flexion could be achieved and patients were able to stabilize their shoulders in the face of active motion. Hand function was routinely ignored.

Gu et al. [56] showed good results in 75% of the musculocutaneous neurotizations with the phrenic, in 50% of the supracapular and axillary neurotizations with motor branches of the cervical plexus, in 55% of the radial neurotizations with the accessory, and in 33% of the median repairs with intercostals. The poor results of the intercostal neurotizations were thought to be due to fewer motor fibers and the long distance between the nerve repair and targets. Nagano et al. [63] reported that the reconstruction of the radial and median nerve with intercostals via nerve grafts also gave poor results, but protective sensation was restored after neurotization of the median nerve. In our series, hand flexion and extension restoration also gave only fair results with neurotization. But in conjunction with free muscle transfers, the results were rated as good in 35% and excellent in 15% of patients. With improvements in preservation of distal muscle targets functional restoration of the hand can only be expected to be better.

Collectively, almost all the reported series have commented on the inferior response following reconstruction with certain muscle groups (shoulder abductors and external rotators, supinators and extensors). Narakas and Hentz [62] felt that this paradox could be partially explained on an embryological basis, wherein there appears to be a built-in preference for restoration of flexors, which are considered more essential for the survival of the organism.

Controversy does surround the optimum level for distal coaptation of nerve grafts during neurotization procedures. Alnot [46] indicated that nerve grafting is more rewarding when the distal coaptation is near the muscle target. In contrast, Bentolila et al. [67] reported improved outcomes when the grafts were coapted distally to the lateral or posterior cord as compared to more distal coaptations near the distal target (i.e., musculocutaneous). We tend to concur with Alnot's observations and prefer to perform the distal coaptation as distally as possible. In turn, the majority of nerve fibers will be directed to the desired target and not lost in random reinnervation [54].

Long graft failures have been minimized with the use of vascularized nerve grafts, i.e., vascularized ulnar based on the superior ulnar collateral vessels [33]. Such grafts are able to maintain their blood supply and have survived transfer even after being placed in a scarred bed. The intraneural environment is optimally preserved and axonal carry-through is not compromised. Birch et al. [72] used the ulnar nerve as a vascular graft based on the ulnar artery, thereby sacrificing one of the main arteries to the hand. All of the results were more favorable as compared to conventional nerve grafting.

Following brachial plexus microreconstruction, pain is dramatically decreased, with the majority of the patients having absolutely no pain or very mild and tolerable pain. This pain decrease is directly related to sensation improvement postoperatively. Restoration of protective sensation allows the patient to recognize the position of the extremity in space and avoid injuries, while any return of afferent input, even if protective, dramatically blocks the nociceptive afferent pathways. Lack of pain permits the patient to focus on extremity rehabilitation with improved dexterity and overall function [54]. Alnot [46] similarly supports the notion that reinnervation restores protective sensibility, particularly in the area served by the median nerve. Narakas and Hentz [62] noted that among 208 patients with severe deafferentation pain secondary to multiple root avulsions, over half of them were pain free following neurotization. Relief of pain preceded functional return by several months.

In the case of global avulsions, those managed late, or when dealing with distal targets such as the hand, free muscle transfers and/or secondary procedures are often necessary in improving the final outcome. Berger [55] stated that only the combination of primary nerve repair with secondary procedures can restore maximum function in a paralyzed extremity. Chuang et al. [73] reported that the best results following free muscle transfer for elbow flexion were obtained after neurotization of the free muscle with three intercostals (78% of the patients had M4). In contrast, poor results were noted following neurotization with accessory, probably because of the use of interposition nerve grafts. Terzis et al. [54] performed 78 free and 29 pedicled muscle transfers to enhance function in a variety of muscle targets. The majority of free muscle transfers were performed for elbow flexion and hand reanimation, and were usually neurotized by a previously "banked" nerve graft that had been coapted to a proximal motor donor nerve during the first stage of nerve reconstruction.

There is little question that brachial plexus root avulsion injuries remain one of the more complex challenges facing reconstructive microsurgeons. Early aggressive, microsurgical reconstruction should be the preferred method of management in most of these injuries. Modern-day, sophisticated nerve reconstruction techniques (neurotizations utilizing every available ipsilateral and contralateral intraplexus and extraplexus donors possible with conventional and/or vascularized nerve grafts), in combination with secondary free functional muscle transfers, may often provide satisfactory outcome even in cases following multiple root avulsions. Amputation should no longer be considered an option too, even in the face of global root avulsion.

Résumé

La plupart des lésions du plexus brachial chez l'adulte sont post-traumatiques secondaires aux traumatismes à haute énergie, en général, des accidents de la route. Chez l'enfant, les paralysies du plexus brachial sont secondaires aux lésions obstétricales, habituellement, une traction excessive sur le plexus pendant un accouchement compliqué ou difficile. La majorité des lésions chez l'adulte et parfois chez l'enfant, sont des avulsions au niveau des racines, responsables de conséquences graves notamment en ce qui concerne des incapacités physiques permanentes de l'extrémité paralysée, une récupération prolongée et un retentissement socioéconomique important. Le traitement moderne des avulsions radiculaires du plexus brachial est basée sur une reconstruction agressive, microchirurgicale, précoce, combinant des neurotisations diverses à des donations extraplexiques homo et controlatérales, l'utilisation des greffes nerveuses vascularisées et également l'utilisation des greffes de muscles libres neurotisées. Lorsque ces techniques microchirurgicales sont appliquées tôt en plusieurs stades (dans les avulsions complètes), on peut observer une récupération importante de la fonction neurologique, surtout chez le patient jeune. Une amputation doit être envisagée seulement lorsque ces techniques microchirurgicales ont échoué.

Resumen

La mayoría de las parálisis del plexo braquial en el adulto son debidas a impactos con gran energía como se producen en los accidentes viarios. En el recién nacido la parálisis del plexo braquial se debe a tracciones excesivas durante un parto complejo o dificil (parálisis obstétricas). La mayoria de las lesiones en el adulto y algunas en los recién nacidos se deben a una avulsión o arrancamiento a nivel de las raíces del plexo braquial, lo que origina una parálisis permanente del miembro afecto y rehabilitaciones muy prolongadas con los subsiguientes costos socio-económicos. En la actualidad, el tratamiento del arrancamiento de las raíces del plexo braquial debe ser precoz, efectuándose una reconstrucción microquirúrgica agresiva del plexo braquial, combinando varios tipos de neurotización con utilización de injertos intraplexus y extraplexus tanto ipsi como contralaterales; se utilizarán también injertos nerviosos vascularizados y por último, injertos musculares libres vascularizados y neurotizados. Cuando se emplean estas múltiples técnicas microquirúrgicas precozmente (en avulsiones completas) pueden obtenerse interesantes resultados por lo que a la recuperación de la función neurológica se refiere, especialmente en pacientes jóvenes. Sólo cuando todas estas técnicas microquirúrgicas fallen puede considerarse la posibilidad de una amputación.

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