MANAGEMENT OF ADULT BRACHIAL FLEXUS INJURIES

ANATOMY :

The brachial plexus is formed by the anterior primary rami of the fifth, sixth, seventh and eighth cervical and the first dorsal spinal nerves on each side. Each spinal nerve is formed by the union of an anterior motor root and a posterior sensory root arising from the respective horns of the grey matter in the spinal cord, the latter showing presence of a spinal ganglion. The anterior and posterior roots unite at the intervertebral foramen and exit from the spinal canal as the spinal nerve. This immediately divides into anterior and posterior primary rami (fig. 1). The posterior branch supplies a twig to the adjacent intervertebral joint and then proceeds to innervate the posterior paraspinal musculature. The anterior primary rami (termed roots of the brachial plexus) join to form the upper (C5C6), middle (C7) and lower (C8T1) trunks (fig. 2). Each trunk divides into anterior and posterior divisions. The anterior divisions form the lateral and medial cords while the posterior divisions form the posterior cord (named according to their positions with respect to the axillary artery behind the pectoralis minor muscle). These eventually divide into the terminal branches (axillary, radial, msculocutaneous, median and ulnar nerves).

BRANCHES

1. FROM ROOTS OF PLEXUS:

LONG THORACIC NERVE: This arises near the roots with a constant C5, C6 contribution with very frequent and variable contributions of C7, C8 and T1 (especially C7). It supplies the serratus anterior muscle.

2. FROM TRUNKS :

SUPRASCAPULAR NERVE : arising from the upper trunk, passing inferiorly, posteriorly and laterally under the suprascapular ligament to supply the supraspinatus and, subsequently, around the spine of the scapula to the infraspinatus muscles.

3. FROM CORDS :

LATERAL CORD : Branches arise to supply the clavicular head of the pectoralis major and pectoralis minor muscles and then to provide the lateral component of the median nerve.

MEDICAL CORD : This gives rise to the medial cutaneous nerves to the arm and forearm, the sternocostal head of the pectoralis major and the medial component of the median nerve. The two components of the median nerve unite behind or just distal to the pectoralis minor in front of the axillary artery.

POSTERIOR CORD : This provides motor branches to the latissimus dorsi (thoracodorsal nerve), subscapularis and teres major (upper and lower subscapular nerves) muscles before terminating as the axillary and radial nerves.

4. COLLATERAL BRANCHES :

These include nerves to the levator scapulae and to the rhomboids which can arise from the C4 (deep cervical plexus) or C5.

5. PHRENIC NERVE :

This may receive a variable contribution from the C5 root.

6. AUTONOMIC NERVOUS SYSTEM FIBRES :

The T1 root communicates with the stellate ganglion carrying the fibers of the autonomic nervous system.

ANATOMICAL VARIATIONS

VARIATIONS IN ORIGINS OF ROOTS

Seddon defined the classic variations as ‘pre-fixed’ when the plexus is formed by C4, C5, C6, C7 and C8 and ‘post-fixed’ when it is formed by C6 to T2.

VARIATIONS IN THE COMPONENTS OF THE CORDS

The anterior division of the middle trunk contriubtes in a variable manner to the formation of the lateral and medial cords giving rise to the different patterns A, B and C noted by Alnot and Huten (fig. 3).

BRACHIAL PLEXUS INJURIES

Excluding direct trauma by means of penetrating injuries, lesions of the brachial plexus are mainly due to stretching forces. These lesions can occur at any level from the spinal cord to the terminal branches (Zones 1 to 5 -–fig. 1) and can be differentiated according to Sunderland’s grades. The stretching force acts on the segments of the plexus between fixed points e.g. the roots at the intervertebral foramina, the suprascapular nerve at the suprascapular notch, the axillary nerve in the quadrilateral space of Velpeau, the musculocutaneous nerve at its entry into the coracobrachialis, the different cords below the coracoid process with the arm in abduction.

Both peripheral and central mechanisms can be distinguished. There are three possible peripheral mechanisms :

1. Downward pull of the shoulder away from the cervical spine. 95% of these lesions occur following motorcycle accidents associated with a fall on the shoulder. The severity of the lesion depends largely on the position of the arm and degree of abduction with maximum stress being caused by retropulsion of the shoulder with the arm in 90 degrees of abduction.
2. Stretching of the upper extremity in maximum abduction which may cause paralysis of C8 and T1.
3. Anteroposterior trauma or dislocation of the shoulder may cause lesions of the cords or the terminal branches of the brachial plexus. This may be accompanied by lesions due to stretching of all the roots.

The central mechanism, secondary to extreme movements of the cervical column caused by violent trauma to the head, can induce intrinsic stretching of the rootlets at the level of the cord without associated lesions of the dura.

The lesions of the brachial plexus can be classified according to their location as supraclavicular i.e. affecting the roots and trunks (75% of cases), and infraclavicular (25% of cases) affecting the cords and their terminal branches. These differ in their causative mechanisms, patterns of lesions seen, possibility of spontaneous recovery or of surgical repair and prognosis for ultimate recovery of function.

SUPRACLAVICULAR INJURIES

These can again be classified as

1. Root avulsions – occurring within the spinal canal at the origins of the anterior and posterior roots from the spinal cord. Being proximal to the dorsal root ganglia, they can be termed as supraganglionic injuries. They are associated with tearing of the dural sleeve with leakage of cerebrospinal fluid and formation of pseudomeningoceles. Non-availability of a proximal stump for surgical repair or reconstruction renders these lesions inoperable. Intraspinal ruptures of the roots prior to the intervertebral foramina can also be included in this group.
2. Extra-foraminal ruptures : These can more or less distally ranging from just after their exit from the spinal canal between the scalenus anterior and medius, lateral to the scalenus anterior, at the level of the trunks or their divisions.

   Very proximal lesions can cause retrograde degenration associated with lesions of the anterior horn cells or with damage to the sensory cells of the posterior root ganglia equivalent to an avulsion injury.

The more distal injuries have a better prognosis following surgical repair and reconstruction.

One must note, however, that supraclavicular injuries can be assoicated with infraclavicular lesions either at or below the level of the cords (15% of all supraclavicular lesions).

Pathologic lesions due to traction are not localised but spread over a significant length of roots or trunks. Hence root avulsions can co-exist with extra-foraminal ruptures. In general, the lower root (C8 and T1) are more prone to be avulsed while C5 and C6 tend to rupture in the interscalenic space (This occurs because the C8 and T1 spinal nerves assume a horizontal position with the arm in abduction and are directly subjected to maximal stretching forces while the C5, C6 and, to a certain extent, C7 nerves have relatively oblique course and suffer traction injuries along their extraspinal course) . Thus the following patterns may be seen :

COMPLETE SUPRACLAVICULAR INJURIES

Total paralysis is the most frequent involving 75-80% of the cases world-wide. Typically, these cases present with avulsion of the C7, C8 and T1 roots and rupture of the C5 and C6 roots (one or two roots may thus be utilisable for surgical reconstruction). Often, all roots are avulsed. Less commonly, the upper and middle trunks are injured.

INCOMPLETE SUPRACLAVICULAR INJURIES

These can be

UPPER PLEXUS PALSIES affecting the C5, C6 +/- C7 roots (20-25% of cases) or

LOWER PLEXUS PALSIES affecting the C8 and T1 roots (2-3% of series world-wide) with sparing of the rest of the plexus.

MANAGEMENT OF SUPRACLAVICULAR BRACHIAL PLEXUS INJURIES

DIAGNOSIS

HISTORY : More than 90% of these injuries occur following traffic accidents with a very large percentage being motorcycle accidents. 90% of these patients belong to the age-group 15-40 years. There is, often, associated head-injury with loss of consiousness for a variable period of time. Multi-stage injuries of the affected extremity with fractures of the clavicle, scapula, humerus, radius and ulna with or without arterial injuries (rupture of the subclavian or axillary artery) may be present.

CLINICAL EXAMINATION

Detailed charting of the motor and sensory deficit at the time of the initial clinical examination is essential in arriving at a diagnosis of the extent of injury and for comparison with subsequent examinations. Affection of the serratus anterior muscle implies a very proximal lesion and hence a poor prognosis. Horner's syndrome represented by ipsilateral myosis, ptosis and enophthalmos indicates very proximal interruption of the C8 and T1 roots.

A positive Tinel's sign in the supraclavicular fossa points to a neuroma in the supraclavicular portion of the plexus and hence a complete interruption of the nerve pathways.

INVESTIGATION

No recovery of an initially complete brachial plexus palsy in the first 2-3 months post-injury or recovery of some muscles (usually distal forearm and hand C8 and T1) with persistent paralysis of the shoulder and elbow motors constitutes and indication for investigation with a view to surgical exploration and repair. In total brachial plexus palsy, investigations are directed towards identification of root avulsions and determination of the probable number of proximal nerve stumps utilisable for grafting. The following investigations help provide this information :

MYELOGRAPHY

Though earlier authors reported signs of dural lesions accompanying interaspinal root injuries of the brachial plexus (Murphey, Hartung and Kirklin – traumatic meningoceles – 1947; Jaeger and Whiteley - 1953; White and Hanelin – 1954; Tarlov and Day – 1954 – defects of myelographic column; Pendergrass, Schaeffer and Hodes – 1956, Mendelsohn, Weiner and Keegan – 1957, Tracy and Brannon – 1958; Heon and Sirois – 1960), it was Yeoman in 1968 who first published a series of myelographies performed in sixty patients with severe brachial plexus injuries. He used Myodil as contrast medium. An axon reflex test was performed in forty patients and the results correlated to the myelographic findings. 78 traumatic meningoceles were noted in the sixty patients. 18 false-positive and 14 false-negative myelographic findings were detected.

With the use of water-soluble dyes and improvement in radiographic techniques, better images are now obtained with a much higher sensitivity and specificity of this procedure. Nagano et al in 1989 have reported their results of metrizamide myelography performed in 90 patients of brachial plexus injuries. They classified the myelographic findings as

N – normal

A1 – slightly abnormal root sleeve shadow

A2 – Obliteration of the tip of the root sleeve with shadow of root or rootlets showing

A3 – Obliteration of the tip of the root sleeve with no root and rootlets shadow visible

D – defect instead of root sleeve shadow

M – traumatic meningocele (fig. 4)

The myelographic findings were confronted with clinical examination of the roots at surgery and somoto-sensory evoked potentials recorded intra-operatively. Their results showed that N is a sign of normality or a post-ganglionic lesion (90.3% correlation). A1 was decided not to be a sign of either post or pre-ganglionic lesion and can occur with partial root avulsion, rupture of the very proximal root, slight intradural scarring or low concentration of contrast medium. A3 is taken as a sign of a pre-ganglionic lesion (97% specificity). A2 may mean rupture of the very proximal root or a partial root avulsion. D also appeared to signify a pre-ganglionic lesion (84.2% specificity). M corresponded to a intraspinal lesion in 96.3% of cases.

David, Alnot, Folinais, Aubin, Jardin and Benacerraf reported their experience with myelography combined with CT myelography in brachial plexus injuries in 1990. 44 patients underwent this procedure and 35 of them subsequently were explored surgically.

They described the CT-myelographic appearance of a normal nerve root from its origin at the spinal cord to its exit at the intevertebral foramen. In addition, images of root sleeve tears with leakage of dye, signs of root avulsion (absence of root shadows arising from the spinal cord) and traumatic meningoceles were defined. They found myelography to have 89% sensitivity while CT-myelography had 97% sensitivity for intra-foraminal root lesions.

ELECTROMYOGRAPHY

An EMG of the posterior paraspinal musculature may help identify a root avulsion. However, the specificity of this procedure is doubtful as these muscles share a multi-segmental innervation. Two successive EMGs of the proximal shoulder muscles (supraspinatus, infraspinatus, latissimus dorsi, deltoid and pectoralis major) will help detect presence or absence of reinnervation not detected by clinical examination. Such reinnervation (in the second or third month) indicates the presence of second degree lesions and hence a good prognosis for spontaneous recovery.

TREATMENT

For a long time, these injuries were considered inoperable and the only treatment offered was one of masterly inactivity awaiting spontaneous recovery failing which an above-elbow amputation was performed with fitting of a prosthetic limb. These prosthese were bulky and cumbersome and were very infrequently used by the patient. This pessimistic attitude was partly due to failed early attempts at surgical repair with positioning of the in lateral flexion for prolonged periods.

Millesi proved that the main deterrent to a useful nerve repair was tension at the suture site and showed the utility of interfascicular nereve-grafting.

Subsequent use of this technique and that of nerve transfers by Kotani, Narrakas, Allieu, Sedel and Alnot along with the use of improved microsurgical techniques and of fibrin glue has shown that surgical treatment of brachial plexus injuries no longer needs to be justified.

COMPLETE PALSIES

AIMS OF SURGERY

1. Stabilization of the shoulder
2. Restoration of the ability to hold objects between the arm and the thorax
3. Restoration of active flexion of the elbow against gravity
4. Recovery of protective sensation over the palm.

TIMING OF SURGERY :

Apart from penetrating injuries, which need to be explored in emergency, traction injuries of the brachial plexus should be of recovery and with a positive Tinel's sign in the supraclavicular fossa.

OPERATIVE TECHNIQUE

The procedure is carried out with the patient in the supine position and the head end raised, the head being turned to the opposite side. The incision runs along the lateral border of the sternomastoid, turns at the clavicle to run parallel to it for a short distance and is then continued distally across the coracoid process into the delto-pectoral groove upto the anterior axillary fold. The infraclavicular dissection proceeds between the deltoid and the pectoralis major muscles with the cephalic vein being retracted laterally. Maintenance of the blood pressure around 85-90 mm of Hg reduces blood loss and facilitates coagulation of bleeders throughout the procedure. The artery to the anterior part of the deltoid arising from the thoraco-acromial trunk needs to be ligated. Retraction of the deltoid and the pectoralis major reveals the pectoralis minor and the combined tendon of conracobrachialis and short head of the biceps inserting on the coracoid process. Dissection then proceeds between these two muscles to expose the musculocutaneous nerve at its entry into the coracobrachialis thus ruling out a distal double lesion of this nerve. This is then traced proximally under the pectoralis minor to the lateral cord, lateral root of the median nerve and the branches to the pectoralis major.

The posterior cord lies behind and lateral to the axillary artery with branches to the latissimus dorsi and subscapularis before terminating as the axillary and radial nerves.

The supraclavicular dissection passes deep to the platysma. The triangular flap marked by the incision is raised to reveal the underlying fat and veins, some of which need to be ligated. The key to this area is the omohyoid muscle, arising from the superior border of the scapula and crossing in front of the brachial plexus. Identification of this muscle and its division at the intermediate tendon of its double belly exposes the upper trunk with the suprascapular nerve. The plexus is usually crossed at this level by the transverse cervical and dorsal scapular vessels which need to be ligated. In case of a more proximal injury of upper plexus, the trunks and the suprascapular nerve are found at the lower level just above or behind the clavicle. In that case, the lateral border of the sternomastoid is retracted to expose the underlying scalenus anterior muscle. The phrenic nerve is identified running on its anterior surface and its intact function is confirmed using a nerve stimulator. The nerve is then followed upwards to where it crosses the C5 spinal nerve at its exit from the intervertebral foramen, The C6 spinal nerve can be found just below and slightly posteriorly. Injury at a more proximal level is ruled out by stimulation of these nerves to check for contraction of the serratus anterior muscle. Some authors (Nagano and Sugioka) routinely record somatic evoked potentials over the contralateral frontal cortex following stimulation of these spinal nerves in order to detect a preganglionic lesion which would preclude their utilisation.

The supraclavicular and infraclavicular areas can be connected by dissecting close to the plexus behind the clavicle and the subclavius muscles (dissection through this muscle is to be avoided to prevent injury to the veins within its mass).

Surgery for brachial plexus reconstruction can involve the following procedures :

NERVE GRAFTING

Following the pioneering work of Millesi, the concept of bridging nerve gaps by interposition of multiple cables of a sensory nerve is now considered routine. The sources of these nerve grafts are usually the sural nerves bilaterally, the medial cutaneous nerve of the ipsilateral forarm and the superficial branch of the ipsilateral radial nerve. These nerves are harvested with atraumatic technique and divided to form multiple cables of adequate length to permit microsuture to the proximal and distal nerve stumps without any tension. One attempts to cover the entire free surface of the proximal nerve stump to provide a conduit for the maximum number of regenerating axons towards the distal effectors

In the presence of large gaps (> 10 cm), the use of vascularised nerve grafts (by free microvascular transfer or pedicled) has been proved pre-ganglionic lesion of the C8 and

T1 roots, the ipsilateral nerve can be used. The portion of the nerve in the arm and proximal forearm can be raised retaining its vascularity from the superior ulnar collateral artery which arises from the brachial artery around 4 cm distal to the lower border of the pectoralis major. It is then turned and the distal end is sutured to the proximal nerve stump (usually C5 or C6 or the upper trunk) while the proximal end (divided above the pedicle) is sutured to the effector nerves (musculocutaneous, median or radial nerves). The forearm portion of the ulnar nerve trunk can be harvested along with the ulnar vessels as a free transfer, the pedicle being then anastomosed to the transverse cervical artery and the external jugular vein in the supraclavicular fossa.

Use of such large nerve trunks as free non-vascularised grafts leads to ischemic degeneration and marked fibrosis which interferes with passage of regenerating axons. These problems are avoided by using a vascularised nerve graft. The problem of inadequacy of available nerve grafts can also be thus overcome. In addition, regeneration is found to progress a faster rate through these nerve trunks though the ultimate functional recovery is not significantly better.

NERVES TRANSFER OR NEUROTIZATION :

In the presence of inoperable root injuries (root avulsion or intraforaminal rupture), distal effectors can be reinnervated using this technique. This implies the division of a normally functioning nerve and its connection by direct suture or nerve-grafting to the distal stump of an irretrievably damaged nerve. The loss of function following division of such a donor nerve is not detrimental or is less detrimental than the possible function regained by reinnervation of the recipient nerve. The difficulty with this technique is to find suitable donor nerves which can provide adequate regenerating axons for the targeted distal nerve. In the study published by Bonnel et al (1979), the number of myelinated fascicles in the different components of the brachial plexus were counted. Their figures were later confirmed by Narrakes (1984) :

C5	7000-33000	Suprascapular	3500
C6	12000-39000	Axillary	6500
C7	16000-40000	Musculocutaneous	6000
C8	14000-41000	Median	18000
T1	10000-35000	Ulnar	16000
		Radial	19000

The sources of donor axons that can be used in complete brachial plexus lesions are

Spinal accessory nerve	1500-1700 myelinated fibers
Intercostal nerves	1200-1300 myelinated fibers each

Motor branches of the deep cervical plexus   4000 myelinated fibers (average)

I) SPINAL ACCESSORY NERVE

The idea of using the spinal accessory nerve to repair the upper brachial plexus is attributed by Narrakas to the American surgeon Tuttle (1921). On 8/11/1912 while operating on a Polish worker with a C5C6 palsy following a knife injury, Tuttle found the proximal nerve stumps severely retracted while the upper trunk was intact behind the clavicle. He could not approximate the spinal accessory nerve divided at the margin of the trapezius muscle to the upper trunk and had to resort to use of the C4 root. Kotani, in 1972, first published his experience with the use of the spinal accessory nerve for neurotization of the musculocutaneous nerve, the upper trunk and the radial nerve. However, he performed direct sutures between the donor and recipient nerves which involved extensive proximal dissection of the musculocutaneous nerve, osteotomy of the clavicle and maintenance of exaggerated positions in the immediate post-operative period.

Since then several units, notably Allieu in Montpellier and Alnot and Sedel in Paris (France), Narrakas in Lausanne (Switzerland), Morelli and Raimondi in Legnano (Italy), have reported on the use of spinal accessory nerve neurotizations for the musculocutaneous, suprascapular, axillary and radial nerves and upper and middle trunks. All these authors use one or two strands of sural nerve graft to connect the proximal and distal nerve stumps.

ANATOMY

This nerve, in its extracranial course, passes through the upper one-fifth of the sternocleidomastoid muscle innervating it. It exists at the posterior border of this muscle, crosses the posterior triangle and enteres the trapezius aroung 5.3 cm above the clavicular insertion. It provides all the motor innervation of the SCM while it shares a variable proportion of the innervation of the trapezius with the trapezius. The accessory nerve is usually uninjured in brachial plexus lesions. It is possible to section this nerve after it has supplied the upper and middle portions of the trapezius and transfer it to the brachial plexus without completely paralysing the trapezius.

Transfer to the suprascapular nerve can be direct or with a very short nerve graft. The two nerves are also more or less equal in size. Transfer to the musculocutaneous nerve involves a nerve graft of 7-15 cm.

RESULTS

Nerve neurotized and no. of cases	Muscle power and results		
	<3	3	>3
MCN (33)	11	10	12
Upper trunk (5)	3	1	1
Posterior cord			
Axillary nerve			
Radial nerve (11)	5	5	1

Thus 22 of 33 patients (67%) recovered useful elbow flexion following transfer of XI to MCN. These figures were further updated in a recent publication by Alnot (1993) where he reports a series of 12 patients of whom 9 (75%) recovered elbow flexion more than or equal to grade 3 while transfer to the suprascapular nerve produced shoulder stability in a corresponding proportion of cases. Transfer to the radial nerve or posterior cord has not proved as successful and has gradually been abandoned.

II) INTERCOSTAL NERVES

Seddon first used the intercostal nerves 3 and 4 via an ulnar nerve graft to neurotize the musculocutaneous nerve achieving useful elbow flexion. Since then, several authors have reported their experience with transfer of intercostal nerves as the sole therapeutic operation (Tsuyama et al 1968, 1972) or along with nerve grafting of other portions of the plexus (Dolenc, 1984; Chuang et al 1992; Nagano et al 1992). Intercostal nerve transfers have also been used to innervate free muscle transfers for elbow flexion and finger flexion (Michael Wood et al 1994).

ANATOMY

The intercostal nerves are the anterior primary rami of the corresponding thoracic spinal nerves. The first thoracic nerve provides a large component to the brachial plexus and then continues as the 1^{st} ICN along the first rib to terminate as anterior and superior branches. The second ICN has a large lateral cutaneous branch to the inner aspect of the arm (intercostobrachial nerve). The third to the eight nerves run initially between the transverse thoracic muscles and the endo-thoracic aponeurosis. Their course lies just under the free border of the corresponding rib and are accompanied by the intercostal vessels. At the mid-axillary line the lateral cutaneous branch separates out, runs along the lower border of the corresponding intercostal space and terminates as anterior and posterior branches. Each intercostal nerve terminates in the parasternal region as an anterior cutaneous nerve.

The lower four ICNs contribute to the innervation of the abdominal musculature as well. Harvesting of the ICNs involves careful subperiosteal dissection around the rib with or without resection of a 1 cm segment. The nerve is identified between the midclavicular and anterior axillary lines and is followed posteriorly with or without the accompanying vessels. Each ICN contributes 1200-1300 myelinated fibers of which around 30% are motor fibers, the percentage being around 40% just distal to the origin of the lateral cutaneous branch. Dissection usually proceeds upto the lateral border of the scapula. Nagano et al prefer direct suture of three ICNs usually 3rd to 5th to the terminal branches of the MCN with the lateral cutaneous branches being grouped together to be sutured to the median nerve or the sensory portion of the MCN. Morelli et al and Celli et al had earlier suggested harvesting the ICNs right upto to their origins and their passage extrapleually into the supraclavicular region but this approach was subsequently given up as being too extensive.

RESULTS

Though initial reports described use of the upper ICNs for the MCN and the lower ones for the radial or median nerves, poor results associated with diffusion of the small number donor axons over several branches led to the concentration of all efforts towards recovery of one single function (elbow flexion).

Chuang et al have reported five stages of recovery as follows :

Induction of chest pain by squeezing the biceps at 3 months post-surgery. Proximal biceps contraction with deep inspiration without elbow joint movement appears at 3-6 months while distal biceps contraction with deep inspiration but without elbow joint movement appears at 12 months. Elbow flexion against gravity appears at 12-18 months post-surgery. The muscle power then improves at the rate of 0.5 kg every 6 months (ability to hold weight tied at the wrist with the elbow at 90 degrees of flexion). The voluntary contraction of the biceps can gradually be performed independently of respiration. This phenomenon has also been confirmed in an elaborate electromyographic and spirometric study reported by Malessy from Leiden in Holland.

Chuang et al reported an overall success rate of 67% for useful elbow flexion while Nagano et al obtained 9 excellent and 19 good results in 35 cases of total root avulsion.

III) ANTERIOR BRANCHES OF THE CERVICAL PLEXUS

Brunelli studied the myelinated fiber content of the supraacromial, supraclavicular and greater auricular nerves and the sensory branches of the transverse cervical plexus and of the motor nerves to the SCM, rhomboid, levator scapulae and trapezius arising from the deep cervical plexus. He found the sensory branches to contribute 3250 fibers while the motor ones contribute an average of 4090 fibers which is much higher than the 1700 fibers provided by the spinal accessory nerve. He reported on the use of these voluntary motor nerves to neurotize the suprascapular and musculocutaneous nerves in a series of 29 patients of which 18 patients had adequate post-op. Follow-up. 11 of these 18 patients recovered useful elbow flexion.

IV) CONTRALATERAL C7 ROOT : Gu et al, in 1992, published their experience using the ventral primary ramus of the C7 spinal nerve of the opposite (normal) plexus, sectioned at the scalenus anterior or at its posterior division, as the donor nerve for regenerating axons. This was then connected to the affected plexus by interposition of a 20 cm long sural nerve graft in two cases and by means of a pedicled or free vascularised ulnar nerve graft (anastomoses with the transverse cervical vessels) in the remaining 45 patients. The rationale of this procedure was the large number of donor axons obtainable and lack of significant motor or sensory deficit produced by division of the C7 nerve on the opposite side. This nerve transfer was the only procedure performed in 15 of these patients. Though the lack of permanent damage on the normal side has been elaborately documented in their initial report and in subsequent clinical and experimental studies (Gu et al 1994), the clinical results are not very clear.

SURGICAL STRATEGIES

COMPLETE PALSIES

NO ROOTS UTILISABLE
XI to musculocutaneous nerve or
XI to suprascapular nerve and ICNs 3 to 5 to musculocutaneous nerve.

ONE ROOT UTILISABLE
XI to suprascapular nerve and C5 to anterior division of upper trunk (if root large and without much fibrosis) or C5 to musculocutaneous nerve (if root small but with no fibrosis).

TWO ROOTS UTILISABLE
XI to suprascapular nerve if injury proximal to upper trunk; C5 to anterior division of upper trunk and C6 to posterior division or vice versa or

C5 to musculocutaneous nerve and C6 to radial nerve proximal or distal to branches to triceps (with interposition of vascularised ulnar nerve).

THREE OR MORE ROOTS UTILISABLE (very rare)

Usually the lesion is distal and grafts are interposed between the proximal stumps of the upper and middle trunks and the lateral and posterior cords.

POST-OPERATIVE CARE

The limb is immobilised against the trunk with the elbow in flexion for three weeks after which gentle mobilisation of the shoulder is permitted. The patient is encouraged to allow the limb to hand free without use of a sling so as to avoid stiffening and contractures of the shoulder in internal rotation. The physiotherapist is instructed to maintain supple mobility of the shoulder, elbow wrist and hand while awaiting recovery of the re-innervated muscles. Electrical stimulation of the paralysed muscles to maintain their mass has been described but has not been proved to be uniformly useful.

The patient is reviewed a month post-surgery to start mobilisation and then every three to six months over the first three years. The progress of the Tinel's sign from the supraclavicular fossa distally is noted. Muscle-building exercises are advised once recovery is clinically visible. Swimming is encouraged for improvement of shoulder girdle muscles. Ordinarily, it takes 15-18 months while suraspinatus recovery can be noted from the sixth post-op month onwards.

INCOMPLETE PALSIES

C5C6 or C5C6C7 LESIONS

One root available :

C5 to ant. division of upper trunk or lateral cord or musculocutaneous nerve.

Tow roots available :

Strategies as above.

No roots available :

XI to musculocutaneous nerve or

XI to suprascapular nerve and ICNs to musculocutaneous nerve

OR

XI to suprascapular nerve and fascicle of intact ulnar nerve directly sutured to the musculocutaneous nerve (Oberlin et al 1994)

OR

XI to suprascapular nerve and branch of medial cord to pectoralis major directly sutured to the musculocutaneous nerve (Brandt and Mackinnon 1993).

INFRACLAVICULAR INJURIES

These distal lsions constitute 25% of brachial plexus injuries undergoing surgery (Alnot et al 1987, 1990).

MECHANISMS OF INJURY :

1. Antero-inferior shoulder dislocation which causes most of the isolated lesions of the axillary nerve and the posterior cord.
2. Violent downward and backward movement of the shoulder, which causes stretching of the plexus.
3. Complex trauma with multiple fractures of the clavicle, the scapula or proximal humerus which causes more diffuse lesions of the cords and terminal branches, often accompanied by vascular damage.
4. Knife or gunshot wounds.

   In addition, 15% of supraclavicular injuries are associated with infraclavicular lesions. These lesions occur when the arm is forced violently into abduction and middle part of the plexus is blocked temporarily in the coracoid region. Terminal branches (musculocutaneous nerve at its entry into the coracobrachialis, axillary nerve in the quadrilateral space, the suprascapular nerve in the coracoid notch) are thus torn and then supraclavicular injuries occur when the head is concomitantly jerked violently to the opposite side.

CLINICAL PICTURE

I) POSTERIOR CORD INJURY

The posterior cord is particularly prone to damage because of its short free course before the first fixed point of the axillary nerve in the quadrilateral space.

This lesion produces weakness in abduction of the shoulder. Some degree of abduction and external rotation by the intact supra and infraspinatus muscles innervated by the suprascapular nerve while the deltoid and teres minor are paralysed. Affection of active internal rotation will depend on the level of lesion and involvement of the branches to the latissimus dorsi and teres major muscles.

Sensory deficit is variable over the lateral aspect of the upper third of the arm and the dorsum of the first web space.

II) ISOLATED OR ASSOCIATED INJURIES OF THE TERMINAL BRANCHES OF THE PLEXUS :

Lesions may involve the axillary nerve either alone or in association with the suprascapular, musculocutaneous or radial nerves. Isolated axillary nerve injuries with shoulder dislocations have a good prognosis. In 80% of cases, these are neuropraxic lesions and recover spontaneously in 4-6 months.

Trauma by violent downward and backward movement of the shoulder leads to more widespread and severe lesions of the cords or terminal branches.

Combined axillary and suprascapular injury produces total paralysis of shoulder abduction and external rotation while an intact suprascapular nerve can permit some abduction which can be confusing.

Axillary and musculocutaneous nerve lesions result in paralysis of shoulder abduction and elbow flexion. Trick movements using gravity (active abduction and antepulsion by the intact supraspinatus and pectralis nerve) or forearm muscles (Steindler phenomenon) have to be watched for.

III) LESIONS OF THE LATERAL CORD AND MEDIAL CORD :

Injury to the lateral cord is rare. Paralysis of elbow flexion and forearm pronators and wrist and finger flexors and sensory loss over the lateral part of the forearm and hand reulsts. Proximal injuries affect the innervation of the upper part of the pectoralis major muscle.

Injury to the medial cord is even rarer. High media-ulnar palsy, complete over the ulnar motor territory and partial over the median territory (particularly FPL and FDP to the index and middle fingers) with or without involvement of the lower part of the pectoralis major along with sensory loss in the area of the medial cutaneous nerve of the forearm should evoke a suspicion of this injury.

Lateral and medial cords may be injured by fractures of surrounding bones (clavicle, scapula, proximal humerus or first rib) which would be revealed on X-ray or in open wounds (glass and knife injuries). Either of these lesions may be accompanied by a radial nerve injury with sparing of the triceps in association with a fracture of the shaft of the humerus.

ASSOCIATED VASCULAR INJURIES

Axillary or subclavian artery rupture with acute ischemia of the affected upper limb necessitates immediate exploration and repair or reconstruction with a vein graft. The nerve lesions are rarely tackled at the same time as it is difficult to determine the exact extent of traction injury to the cords and terminal branches. However, subsequent nerve exploration and repair is rendered more difficult by the fibrosis resulting from the emergency surgery. Hence, it is helpful to identify the different nerve trunks injured and to tag them at some distance from the reconstructed vessels.
Vascular trauma in the absence of acute ischemia points towards early exploration for the nerve injuries with vascular reconstruction being performed at the same time This improves the trophicity of the extremity and the prognosis of muscular recovery following nerve repair.

IATROGENIC LESIONS

These may occur during excision of nerve tumours e.g. Schwannoma affecting the ingraclavicular plexus or during surgical procedures for recurrent shoulder dislocation such as the Latarget technique. The posterior cord and the musculocutaneous nerve are prone to injury during the approach or may be strangulated during muscle repair. Abnormal post-operative pain should arouse one's suspicion. Paralysis of active elbow flexion or shoulder abduction is an indication for immediated exploration

THERAPEUTIC INDICATIONS

These are base on repeated clinical examinations, electromyograoms and cervical myelography and CT-myelography.
Intact serratus anterior and supra and infraspinatus muscles, absence of a Tinel's sign in the supraclavicular foss and a normal myelogram points to an infraclavicular lesion. Knowledge of common clinical patterns of injury is helpful.
In 60% of infraclavicular lesions, recovery is spontaneous which is heralded by EMG signs of reinnervation. The rate of return of function depends on the distance from the lesion to the effector muslce. Absence of clinical or electromygraphic recovery indicates surgical exploration as nerve grafting or neurolysis produces much better results here than with supraclavicular lesions.

SUPPLEMENTARY SURGERY

COMPLETE SUPRACLAVICULAR BRACHIAL PLEXUS PALSIES

Nerve reconstruction in these cases frequently results in a stable shoulder with some abduction (supraspinatus), elbow flexion (biceps) with or without shoulder antepulsion (pectoralis major). However, the recovery of active external rotation is quite poor. In such cases, as the patient flexus his elbow, the forearm slides along the trunk which appears ungainly and is not useful plane, a derotation obsteotomy of the humerus at the upper third-middle third junction can be performed. This can be combined with a transfer of latissmius dorsi or teres major (if these have recovered adequately) to the infraspinatus tendon insertion to provide some active external rotation of the shoulder.

The automatic supination associated with recovery of the biceps with a paralysed forearm and hand may need to be rectified by fusion of the wrist and distal radio-ulnar joint in pronation.

Similarly, the tendency of the paralysed fingers to assume a clawed position can be corrected by fusion of the proximal interphalangeal joints of the long fingers in a better position.

Recovery of brachioradialis or wirst extensors can be utilised to achieve finger flexion by transfer to the flexor policis longus and flexor profundus tendons.

Sometimes, simultaneous recovery of triceps (following grafting to anterior and posterior divisions of upper trunk) produces disturbing co-contractions interfering with elbow flexion. In such cases, triceps to biceps transfer (Carool, 1952) can be performed.

INCOMPLETE PASLIES

Failure of recovery of elbow flexion against gravity (grade II or II+) following nerve surgery, can be raised to grade III by performing a Steindler's transfer of the common flexor origin with the medial epicondyle 4 cm proximally on the humeral metaphysis. In some cases, this can be supplemented with a shift of the costal origin pectoralis minor to the biceps tendon.

Absence of active wrist extension with intact finger flexion in C5C6C7 palsies can be treated by a tenodesis of the digital extensors at the distal radius.

OVERALL RESULTS OF SURGERY OF THE BRACHIAL PLEXUS

Narakas, Allieu, Alnot, Brunelli, Merle, Santos-Palazzi and Sedel, together, presented their results in the monograph of the French Hand Society (G.E.M.) on Brachial Plexus Lesions in 1990.

Other significant reports, in recent years, have been those of Nagano et al (1992), Alnot et al (1992) and Chuang et al (1992), Chuang et al have classified their cases as all roots avulsed (35 patients) and upper root avulsions (31 cases). However, the results of useful elbow flexion (44 of 66 patients) following intercostal nerve neurotization have not been separated according to complete and incomplete initial palsies.

Thus, classified results of nerve reconstruction are available only for complete supraclavicular palsies.

ALL ROOTS AVULSED

1) GEM – 15 cases studied.

Functions	No. of cases	Useful result (gr. 3 or more)	Failures
Shoulder addn	15	7	8
Shoulder abdn	15	8	7
Elbow flexion	15	11	4
Wrist flexion	15	1	13
Pollici-digital pinch	15	0	15

Sensation

5 of these patients recovered protective sensation over the lateral forearm and thumb and radial one-third of the hand.

ii) Nagano et al :

Elbow	35	38	7

iii) Alnot et al :

Elbow flexion	12	9	3

ONE ROOT UTILISABLE (C5 ruture, C6-T1 avulse)

i) GEM – 24 cases

Shoulder addn	18	6	12
Shoulder abdn	18	7	11
Elbow flexion	24	11	13
Active wrist flexion	24	0	24
Pollici-digital pinch	24	0	24

Protective sensation over radial half of forearm and hand in 16 of the 24 cases.

ii) Nagano et al : 9 cases

Elbow flexion	9	8	1

iii) Alnot et al : 23 cases

Elbow flexion	23	17	6
Shoulder addn	16	12	4
Shoulder abdn			
(XI-SS or C5-SS)	16	7	9
Finger and/or Wrist flexion	16	5	11

TWO ROOTS UTILSABLE (C5C6 rupture, C7-T1 avulsed)

i) GEM – 24 cases

Shoulder addn	22	12	10
Shoulder abdn	22	6	16
Elbow flexion	24	7	17
Hand to mouth	22	4	18
Wrist flexion	22	4	18
Pollici-digital pinch	22	2	20

Protective hand sensation in 17 of the 24 patiens.

ii) Nagano et al : 9 cases

Elbow flexion	9	8	1

iii) Alnot et al : 9 cases

Elbow flexion	9	7	2

(the two failure recovered good triceps function which was then transferred to the biceps to obtain elbow flexion against gravity)

Shoulder addn	8	6	2
Shoulder abdn	7	3	4
Wrist flexion	8	3	5
Wrist extension	5	1	4

THREE ROOTS UTILISABLE (C5C6C7 distal ruptures, C8T1 avulsed)

i) GEM – 18 cases

Shoulder addn	18	13	5

Shoulder abdn	18	4	14
Elbow flexion	18	12	6
Hand to mouth	18	10	8
Wrist flexion	18	5	13
Finger flexion	18	1	17
Pollici-digital pinch	18	2	16

ii) Alnot et al : 6 cases

Elbow flexion	6	6	0
Shoulder addn	6	6	0
Shoulder abdn	6	2	4
Wrist flexion	4	1	3

Thus, it is evident that, in complete supraclavicular palsies, useful elbow and shoulder function can be obtained in 65-75% of patients following nerve surgery. However, irrespective of the number of graftable roots, the distal hand function recovered is quite poor. Protective hand sensation is recovered in a majority of cases.

INFRACLAVICULAR PALSIES

ALNOT ET AL (1984, 1987)

i) Isolated musculocutaneous nerve lesions – 7 patients Elbow flexion grade 3+ to 4 in all patients.

ii) Cord lesions – 73 patients.

59 patients with posterior cord lesions treated by neurolysis or graft. Associated lesions of median and musculocutaneous nerves occurred in 30% of these patients. Results not clearly analysis because of associated lesions and combined procedures (neurolysis and grafts) in the same patient.

iii) 25 patients with axillary nerve lesions – nine associated with other injuries (4 suprascapular nerve and 5 musculocutaneous nerve) and 16 isolated injuries. Results were good after neurolysis of the suprascapular nerve and graft of the axillary nerve whereas sholder abduction was disappointing in associated axiallary and suprascapular nerve ruptures. Satisfactory shoulder abduction and elbow flexion was obtained in the five patients with combined axillary and musculocutaneous nerve ruptures.

11 of the patients with isolated axillary nerve rupture who underwent a nerve graft had good recovery at 1 year follow-up.

SEDEL 1982

He reported on eight patients in whom at least one main trunk was grafted and five patients with lesions in continuity.

Uniformly good results were obtained for elbow flexion following lateral cord or musculocutaneous nerve grafting. Similarly radial nerve grafting produced triceps and wrist extensor recovery in each case. However, recovery of finger flexors as well as that of thenar muscles following median nerve and lateral cord grafting was poor.

Neurolysis of lesions in continuity uniformly produced almost complete recovery.

PAIN IN BRACHIAL PLEXUS INJURIES

One of the most distressing features of avulsion lesions of the brachial plexus is the severe pain felt by most of these patients. The onset of this pain may be immediate or delayed.

The pain is highly characteristic and has two distinct features. One is a constant background pain, usually described as burning (as if the arm is in a vise or is being hit repeatedly with a hammer) or, at times, as feeling like a razor blade cutting through the skin. This pain persists throughout the day, in invariably present if waking at night, and hardly ever varies in intensity. The second feature is pain characterised by periodic sharp paroxysms that shoot through the arm, lasting a few seconds at a time. These can sometimes be more difficult to deal with than the constant background pain, for they take the patient by surprise and may cause him to cry out or drop objects. The frequency of these paroxysms varies from many shooting pains per hour to 2-3 per day or a few per week. Over a period of time, the paroxysms tend to become less frequent, but in a significant proportion of patients, they represent a very severe disability. Cold weather and intercurrent illness are potent aggravating factors. Emotional stress, too, can increase the pain.

Gripping the arm or moving the fingers may temporarily relieve the pain. The single most constant feature in relieving pain or at least making it more bearable is distraction, such as being deeply involved in work or in absorbing hobbies.

MECHNISM OF CAUSATION OF PAIN

Pain in brachial plexus injuries is explained on the basis of the neurophysiological cocept of deafferentation pain which applies to all painful sensation arising from any part of the body whose usual afferent information has been partially or completely interrupted by a lesion of the peripheral or central somatosensory pathway.

CHANGES IN THE PERIPHERAL NERVOUS SYSTEM

Complete severance of a nerve without repair or a poor repair results in the formation of a neuroma. The regenerating axons and demyelinated fibers at the site of injury are particularly sensitive to pressure (Tinel's sign), ischemia and adrenaline and noradrenaline and begin to produce spontaneous nervous discharges after a few days. Abnormal spontaneous cellular discharge is also observed in dorsal root ganglia after nerve injury.

CHANGES IN THE CENTRAL NERVOUS SYSTEM

Massive degeneration of afferent terminals can be seen in the spinal cords after lesions of dorsal roots and, to a lesser extent, after severing the peripheral nerves. Inhibition usually exerted by AB afferent fibers on transmission of nociceptive messages by C fibers is reduced. The neurons in layers four, five and six of the dorsal horns become responsive to other afferent fibers of closely situated intact nerves and develop new peripheral receptive areas. This can explain the appearance of induced pain in the upper limb when stimulation is exerted by touch or pressure of the thorax.

Abnormal spontaneous cellular activity can be found in convergent tactile and nociceptive neurons in the dorsal horn of the spinal cord during the first 2 months following injury. Later on, a spontaneous abnormal epileptic type of activity can be recorded in the thalamic and somesthesic cortical areas representing the projections of the deafferented limb.

These neurophysiologic considerations can explain certain facts concerning therapy :

1. Narcotic and non-narcotic analgesics and NSAI Drugs are not useful unless inflammatory reactions enhance the effects of nerve injury.
2. Amputation or disarticulation does not alter the pain that persists in the missing limb.
3. Reconstructive nerve surgery, when possible and successful, results both in motor recovery and sensitive reafferentation of the central nervous system.
4. Transcutaneous or medullary electrical neurostimulation is possible only in partial injuries of the brachial plexus (distal lesions of two nervous trunks or proximal lesions involving one or two roots). Stimulation of large fibers peripherally or of the medullary dorsal column produces an inhibitory control in the dorsal horn of the spinal cord.

5. Antiepileptic drugs such as clonazepam (1-4 mg/day) or Carbamazepine (300-600 mg/day) can control the medullary, thalamic or cortical epileptic activity that is responsible for the impressions of electric shocks, painful shots or paroxystic painful attacks such as crushing pain.
6. Tricyclic antidepressants, in addition to their antidepressor effect, seem to have an analgesic effect, probably mediated by their influence on monaminergic descending inhibitory systems in the spinal cord.
7. Some mental techniques such as relaxation or hypnosis, probably acting through central inhibitory pathways, can help control permanent pain and aggravation of pain by emotional stress. However, they can not control paroxystic pain.

NONOPERATIVE TREATMENT OF PAIN

1. Antiepileptic drugs such as clonazepam (1-4 mg/day) or Carbamazepine (300-600 mg/day) (as mentioned above) – If successful in controlling pain, they should be continued for 6-12 months.
2. Tricyclic antidepressants such as Imipramine (4-75 mg/day).
3. Transcutaneous nerve stimulation : This needs to be given for many hours a day, for weeks on end, before it can be judged as ineffective. The effect is cumulative and technique is all important. The electrodes are placed just proximal to the most proximal site of anesthesia. It is essential to apply the electrodes over an area where there is sensory input, as placement over anesthetic areas is obviously useless. For a total lesion, this means placing an electrode over the inner side of the arm, over the T2 input and over the neck or the shoulder over the C2, C3 or C4 deramtome. If C5 or C6 roots are spared, the electrodes can be placed over the arm. Patients are encouraged to wear the stimulator for several hours a day. Treatment is not stopped until the patient has reported no change at all after a full week's trial utilising different positions and different settings of the parameters (pulse widthm amplitude and repetition rate)

SURGICAL TREATMENT OF PAIN

In 1979, Nashold and Ostdahl described a procedure for intraspinal coagulation of the dorsal root entry zone (DREZ) as a treatment of severe pain reacting poorly to conventional therapy. This destroys the area of the spinal cord where the spontaneous on going firing of neuronsm released from afferent inhibition, is taking place. Wynn Parry, Frampton and Monteith (1987) have reported dramatic relief of pain in 17 of the 22 patients for Nervous Diseases, London for Nashold's procedure. This pain relief was maintained for 2 years and more.

A further series of good results (20 out of 24 patients having >75% relief of pain) was reported by Bruxelle, Travelers and Thiebaut in 1988. These authors have slightly modified the original technique to destroy the greatest possible proportion of the deafferented dorsal horns at the level of avulsion.

After performing an extensive cervical laminectomy and opening the dura, the arachnoid is dissected under magnification and the dorsolateral sulcus is identified. The level is determined by recognizing the attached roots below and above the avulsed area. A series of forcal radio frequency heat lesions are produced by a tiny 0.25 mm electrode inserted every 2 mm into the dorsal root entry zone. Hemostasis (75 degrees for 15 seconds) is controlled by a thermocouple. To produce complete destruction of the abnormal dorsal horns, a 2.5 mm deep incision is performed with a micro razor blade.

Pain relief is noted in the immediate post-operative period and is maintained at long-term follow-up.

COMPLICATIONS

1. CSF fistula
2. Slight post-operative sensory or motor deficit of the homolateral lower limb which may persist in some cases without actually impairing normal gait.
3. Sensory disturbances may extend to the thoracic region with mild intermittent constrictive sensations.

CONCLUSION

Surgical repair of traumatic brachial plexus palsies improves the prognosis. It is more effective for patients who sustain infraclavicular lesions or for supraclavicular lesions when at least two roots can be used for grafting. If only nerve transfer is possible, there is still some improvement. Concentrating on grafting one distal nerve gives better results.

BIBLIOGRAPHY
MICRO RECONSTRUCTION OF NERVE INJURIES
EDITOR – JULIA K. TERZIS
1987, W.B. SAUNDERS COMPANY

ALNOT J.Y. – Traumatic Paralysis of the Brachial Plexus Preoperative Problems and Therapeutic Indicatios. 325-346

ALNOT J.Y. – Infraclavicular Lesions. 393-402

MILLESI H. – Brachial Plexus injuries – Management and Results. 347-360

BONNEY G. BIRCH R., JAMIESON A.M., EAMES R.A. – Experience with Vascularised Nerve Grafts. 403-414.

ALLIEU Y., PRIVATE J.M., BONNEL F. – Paralysis in root avulsions of the Brachial Plexus : Neurotization the Spinal Accessory Nerve. 414-424

DOLENC V.V. – Intercostal Neurotization of the Peripherals Nerves in Avulsion Plexus Injuries. 424-434

BRUNELLI G. – Neurotization of Avulsed Roots of the Brachial Plexus by means of Anterior Nerves of the Cervical Plexus. 435-436

NARAKAS A.O. – Thoughts on Neurotization or Nerve Transfers in Irreparable Nerve Lesions. 447-454

WYNN PARRY C.B., PRAMPTON V., MONTEITH A. – Rehabilitation of Patients following traction lesions of the Brachial Plexus. 483-496

SEDDON H.J. – Surgical Disorders of the Peripheral Nerves, 1st Ed. Edinburgh, Churchill Livigstone, 1972.

ALNOT J.Y. and HUTEN D. – La systemisation du. plexus brachial. Rev. Chir. Orthop., Vol. 68(1) : 27-34, 1977.

MURPHEY F., HARTUNG W. and KIRKLIN J.W. – Myelographic demonstration of avulsing injry of the brachial plexus, American Journal of Roentgenology and Radium Therapy, vol. 58, p. 102, 1947.

JAEGER R. and WHITELEY W.H. – Avulsion of the brachial plexus, Report of six cases, Journal of the American Medical Association, vol. 153. P. 633, 1953.

WHITE J.C. and HANELIN J. – Myelographic sign of Brachial Plexus Avulsion. Journal of Bone and Joint Surgery, vol. 36-A. p. 113, 1954.

TARLOV I.M. and DAY R. – Myelography to help localize Traction Lesions of the Brachial Plexus. American Journal of Surgery, vol. 88, p. 266, 1954.

PEDNERGRASS E.P., SCHAEFFER J.P. and HODES P.J. – The Head and Neck in Roentgen Diagnosis. Second edition. Vol. 2, p. 1755. Oxfor : Blackwell Scientific Publications.

MENDELSOHN R.A., WEINER I.H. and KEEGAN J.M. – Myelographic demonstration of Brachial Plexus Root Avulsion. Archives of Surgery, vol. 75, p. 102, 1957.

TRACY J.F. and BRANNON E.W. – Management of Brachial Plexus Injuries (Traction Type). Journal of Bone and Joint Surgery, vol. 40-A, p. 1031, 1958.

HEON M. and SIROIS J. – La valeur du myelogramme. Comme aide diagnostique et pronostique dans les lesions traumatiques du plexus brachial, Canadian Journal of Surgery, vo. 3, p. 112, 1960.

YEOMAN P.M. – Cervical Myelograph in Traction Injuries of the Brachial Plexus. Journal of Bone and Joint Surgery, vol. 50B, no. 2, pp. 253-260, 1968.

NAGANO A., OCHIAI N., SUGIOKA H., HARA T. and TSUYAMA N. – Usefulness of Myelography in Brachial Plexus Injuries. Journal of Hand Surgery vol. 14-B, no.1, pp. 59-64, 1989.

LES PARALYSIES DU PLEXUS BRACHIAL MONOGRAPHIES DU GROUPE D'ETUDE DE LA MAIN EXPANSION SCIENTIFQUE FRANCAISE (Publishers) 1990

DAVID M., ALONT J.Y., FOLIANIS D., AUBIN M.L., JARDIN C. and BENACERRAF R. – Aspects radiologiques et correlations anatomocliniques des lesions radiculaires lors des paralysies traumatiques du plexus brachial de l'adulte, 116-122.

ALNOT J.Y., OBERLIN C. – Anatomie chirurgical du nerf spinal, 37-42.

BRUNELLI G. and BUNELLI F. – Anatomie de la 3eme anse du plexus cervical, 43-45.

HOLLE J., FREILINGER G. and SULZGRUBER C. – Anatomie chirurgicale des nerfs intercostaux. La distribution des fibres motrices et sensitives, 46-48.

NARAKAS A.O., ALLIEU Y., ALNOT J.Y., BRUNELLI G., MERLE M., SANTOS-PALAZZI, SEDEL L. – Les paralysis supraclaviculaires totales – Possiblities chirurgicales et les resultats, 130-161.

ALNOT J.Y., NARAKAS A.O., RAIMONDI P.L. and MORELLI E. – Paralysies traumatiques du plexus brachial de l'adulte. Lesions retro- et infraclaviculaires, 208-216.

CLINICAL ORTHOPAEDICS AND RELATED RESEARCH, VOL. 237, 1988.

LEFERT R.D. – Clinical Diagnosis, Testing and Electromyographic study in Brachial Plexus Traction Injuries, pp. 24-31.

MILLESI H. – Brachial Plexus Injuries – Nerve grafting, pp. 36-42.

BRUXELLE J., TRAVERS V. and THIEBAUT J.B. – Occurrence and Treatment of Pain after Brachial Plexus Injury, pp. 87-93.

SEDEL L. – The results of surgical repair of brachial plexus injuries. Journal of Bone and Joint Surgery, vol. 64B, pp. 54-66, 1982.

SUGIOKA H. – Evoked Potentials in the Investigation of traumatic lesions of the Peripheral Nerve and the Brachial Plexus. Clinical Orthopaedics and Related Research, vol. 184, pp. 84-92, 1984.

ALNOT J.Y. – DAUNOIS O., OBERLIN C., BLETON R. – Les paralysies totales du plexus par lesions supraclavculaires. Revue de Chirurgie Orthopedique, vol. 78, pp. 495-504, 1992.

BONNEL F., ALLIEU Y., SUGATA Y. and RABISCHONG P. – Bases anatomo-chirurgicales des neurotisations ppour avulsion radiculaires due plexus brachial. Anat. Clin. Vol. 1, pp. 291-296, 1979.

KOTANI P.T., MATSUDA H. and SUZUKI T. – Trial surgical procedures of nerve transfers to avulsion injuries of the plexus brachialis. Orthopaedic Surgery and Traumatology. Proceedings of the 12th Congress of the International Society of Orthopaedic Surgery and Traumatology (SICOT) p. 348, Tel Aviv, 1972.

CHUANG DAVID CHWEI-CHIN, YEH MING-CHUNG and WEI FU-CHAN – Intercostal nerve transfer of the musculocutaneous nerve in avulsed brachial plexus injuries : Evaluation of 66 patients. Journal of Hand Surgery, vol. 17A, pp. 822-828, 1992.

NAGANO A., OCHIAI N. and OKINAGA S. – Restoration of elbow flexion in root lesions of brachial plexus injuries. Journal of Hand Surgery, vol. 17A, pp. 815-821, 1992.

GU Y.D., ZHANG G.M., CHEN D.S., YAN J.G., CHENG X.M. and CHEN L. – Seventh Cervical nerve root transfer from the contralateral healthy side for treatment of brachial plexus root avulsion. Journal of Hand Surgery, vol. 17B, pp. 518-521.

BRANDT K.E. and MACKINNON S.E. – A technique for maximising biceps recovery in brachial plexus reconstruction, Journal of Hand Surgery, vol. 18A, pp. 726-733. 1993.

KRAKAUER J.D. and WOOD M.B. – Intercostal nerve transfer for Brachial Plexopathy. Journal of Hand Surgery, vol. 19A, pp. 829-835, 1994.

CARROL R.E. and HILL N.A. – Triceps transfer to restore elbow flexion : a study of fifteen patients with paralytic lesions and arthrogryposis. Journal of Bone and Joint Surgery, vol. 52A, pp. 239-344, 1970.

CELLI L., BALLI A., de LUISE G. and ROVESTA C. – La neurotizzazione degil ultimi nervi intercostali, mediante traplante nervoso pedunculato, nelle avulsioni radicolari del plesso brachiale. Chir. Organi, Mov. Vol. 64, pp. 461, 1978.

TSUYAMA N. and HARA T. – Intercostal nerve transfer in the treatment of brachial plexus injury of root avulsion type. Excerpta Medica 291, pp. 351, 1972.

NARAKAS A.O. – Clinics in Plastic Surgery, vol. 11, p. 154, 1984.

PAJARDI G., MORELLI E. – Les lesions traumatiques du plexus brachial. Traitment microchirurgical. J. Chir. Vol. 122, pp. 305-309, 1985.

OBERLIN C., BEAL D., LEECHAVENGEVONGS S., DAUGE M.C. and SARCY J.J. – Neurotization of biceps muscle using a part of ulnar nerve for C5C6 avulsion of the brachial plexus. Case report and anatomic study. Journal of Hand Surgery, vol. 19A, pp. ….., 1994.