REVIEW ARTICLE

Official Journal of the
Neuroscience Society of Nigeria
(NSN)

https://doi.org/10.47081/njn2018.9.2/001
ISSN 1116-4182

Brachial Plexus Injuries in Adults: Guidelines and Management in our Experience

Debora Garozzo

Brachial Plexus and Peripheral Nerve Surgery Unit, Neuro Spinal Hospital, Dubai, United Arab Emirate

Received:* ……………. *January 2018
Accepted:* ……………. *June 2018

ABSTRACT

According to the data published in current medical literatures, brachial plexus injuries affect slightly more than 1 % of multi-trauma patients. Motorcycle accidents were the leading cause associated with the occurrence of these lesions that often lead to severe disability mostly in young individuals. The vast majority of these patients were young males between 15 and 35 years. After the injury, approximately 95% of these patients suffer from excruciating pain that poses an additional burden on the quality of life, already disrupted by the functional impairment of the upper limb. Despite the statistical rarity, brachial plexus injuries clearly have a remarkable impact on the community. Today with new techniques in the role of surgical procedures, the quality of life of many of these patients can be improved especially in partial lesions allowing functional recovery, rescuing these young individuals from disability and improving their lifestyle. Early diagnostic assessment with prompt referral to the surgeon is crucial to obtain a positive outcome. Physiotherapy plays a vital role in the rehabilitation process. The Author aims to illustrate guidelines in the management and surgical treatment of brachial plexus injuries as gained in over 20 years of experience in medical practice.

Key words: *Brachial plexus injuries, Scapular fracture, Clavicular fracture, Root avulsions, 3D MRI, Nerve transfer and Nerve graft*

INTRODUCTION

Brachial plexus palsies are the most common traction injuries in traumatic events causing a sudden, excessive widening of the head-shoulder angle or a forceful distraction of the upper limb away from the trunk. Epidemiological studies are few, but available data are mostly reports from North America. It is reported that about 1-5% of multitrauma patients presenting to a tertiary trauma facility had sustained brachial plexus injuries (BPIs) mostly as a result of two causes; motorcycle and snowmobile accidents (Midha 1997).

In 2006, a national prevalence of approximately 350.000 patients and an annual incidence of roughly 3500 new BPIs per year were estimated in the United States of America (USA). There are increasing incidences of these lesions (Narakas 1985; Ferraresi et al. 1994; Jain et al. 2012; Kaiser et al. 2012; Garozzo et al. 2013; Faglioni et al. 2014; Park et al. 2017), due to the spreading motorization in developing countries (especially in South-East Asia) and the ongoing warfare in the Arab world.

The compulsory use of safety helmets has resulted in a higher survival rate after motorcycle accidents in comparison with the past. But helmets may even contribute to increasing BPIs incidences as they increase the weight of the head, facilitating the forceful widening of the head-shoulder angle during trauma. It is reported that after enforcing the use of safety helmets by law in Italy, there was a significant increase (32%) in severe, almost irreparable lesions in comparison with previous data reported in the

Correspondence: Debora Garozzo, Head, Brachial Plexus and Peripheral Nerve Surgery Unit, Neurospinal Hospital, Jumeirah Beach Road, P.O. Box 71444 Dubai, United Arab Emirates. E-mail: debora.garozzo@nshdubai.com; +971-4-3420000

literature (Ferraresi et al. 1994).
Male patients aged between 15 and 35 years largely predominate (Narakas 1985; Ferraresi et al. 1994; Midha 1997; Jain et al. 2012; Kaiser et al. 2012; Garozzo et al. 2013; Faglioni et al. 2014; Park et al. 2017). A favourable evolution can occur in some cases with neurapraxic injuries, but root avulsions (Fig.1) are present in more than 70% of cases (Narakas 1985; Ferraresi et al. 1994; Garozzo et al. 2013; Garozzo 2017; Park et al. 2017), thus ruling out any possibility for spontaneous recovery in the vast majority of these patients.
In addition to functional impairment, BPIs are associated with pain in 70 to 95% of cases (Teixeira et al. 2015; Ciaramitaro et al. 2017; Park et al. 2017), especially in cases of multiple root avulsions.

Table 1: Nerve Transfers

Donor nerve	Main recipient nerve(s)	Remarks on the procedure and its indications	Pros	Cons	The Author's experience
Spinal accessory nerve (XI)	SS	XI-SS nerve transfer can be performed via anterior or posterior approach: according to some Authors the latter provides better results, due to its proximity to the target muscles and the decompression of the SS at the first notch.	Excellent donor for the SS	XI-MC transfer requires an interposition graft.	The XI-SS nerve transfer is our preferred strategy to restore the spinati muscles. We usually perform it via anterior approach: a posterior approach is used only when supraclavicular exploration reveals a distal rupture of the SS that rules out a direct XI-SS suture.
	MC	XI-MC nerve transfer is generally used in complete palsies with multiple avulsions and no other option to re-innervate the biceps. In such cases, shoulder re-innervation is not performed due to lack of donors for the spinati.		Shoulder extra rotation has a less favourable outcome in comparison with shoulder abduction	In our opinion XI-MC nerve transfer should be abandoned: outcome is poor in the majority of cases. Moreover if the spinati are not re-innervated and the trapezius is denervated (thus ruling out indication for shoulder arthrodesis), biceps re-innervation, is unlikely to be functional without good shoulder stability.
Phrenic nerve	MC	Contraindicated in children younger than 3 years for the high rate of complications (infections, thoracic cage deformities, etc.) Harvest can be performed from the supraclavicular area or via VAT from the thorax	Valid donor	No available follow up studies on respiratory function in elderly patients	Not used for fear of respiratory complications when the patient reaches the old age
Pectoral nerves	MC	Adduction is unaffected as supported by other muscles	Valid donor	Denervation of the pectoral muscles	In upper palsies, complete denervation of the pectoral muscle remarkably affects cosmetics so we usually prefer to resort to other strategies
Thoraco-dorsal nerve	MC AX	Adduction is unaffected as supported by other muscles	Valid donor	Denervation of the latissimus dorsi	This transfer is our preferred strategy to re-innervate the axillary nerve in upper palsies and we consider it superior to Somsak's procedure (see Table 2)
Subscapular nerves	AX MC	Intra-rotation is unaffected as supported by other muscles	Valid donor	No cons	When available, we use it to re-innervate the axillary nerve
Intercostal nerves	MC Radial nerve, AX LTN	Being the first 2 intercostal nerves mainly sensitive, surgeons usually harvest from the III intercostal nerve	Valid donors Respiratory function is not affected even in cases of phrenic nerve palsy	Not to be used in cases of multiple rib fractures, cervical cord injury or Brown Sequard injury	Largely used in panavulsive injuries (see text)
Contralateral C7 (cC7)	Median nerve/ lower trunk Upper trunk	According to the technical variants, the whole cC7 or one of its divisions (preferably the posterior division) can be harvested When cC7 is coapted to the lower trunk, humeral shortening up to 4 cm can be necessary Autonomization of the re-innervated limb from synchronous movement of the donor limb requires at least 5 years	High number of axons	Safely harvested in most patients, it occasionally results in deficits of the extensors. Possibility of a later recovery is described. Pain and paresthesias in the radial territory of the hand in the donor limb can be permanent Autonomization is not guaranteed	Our criteria in selecting the patients for this procedure include: ✓ complete brachial plexus palsies with multiple avulsions, ✓ slim patients younger than 30 years, ✓ no major head injury, ✓ brachial plexus micro reconstruction within 6 months from the trauma. We consider cC7 a salvage-like procedure in panavulsive injuries with no possibilities to use the intercostal nerves in order to restore shoulder and biceps. cC7 transfer to regain some hand function was also performed but outcome was not rewarding. Harvest of cC7 was always performed under intra-operative neurophysiological monitoring in order to avoid possible damage to the donor limb. Experience with Gu's technique mainly

XI= spinal accessory nerve, SS=suprascapular nerve, MC= musculocutaneous nerve, AX=axillary nerve, LTN= long thoracic nerve, VAT =video –assisted thoracotomy

Table 2: Distal Neurotizations

The technique and its historical background	Donor fascicles	Recipient nerve	Remarks	Pros	Cons	The Author's experience
"Oberlin's transfer" **Introduced by Oberlin in the early 90s, it revolutionized brachial plexus surgery**	Fascicles for the FCU from the ulna nerve at the arm	The muscular branches of MC	It can be used in C5,C6 avulsions and even in late referral cases	It can be used even in cases of avulsions of the upper roots regaining excellent biceps function	Only re-innervation of the biceps	We started to apply this nerve transfer according to the original description, later on we modified it using the whole MC as recipient and occasionally choosing the donor fascicles from the median nerve.
The double neurotization. **Modified technique of the above procedure introduced by Oberlin in 2004 and largely popularized by Mc Kinnon**	Fascicles for the FCU from the ulna nerve and fascicles for the pronator muscles from the median nerve	FCU fascicles are coapted to the muscular branches of the MC Fascicles from the median nerve are coapted to the brachialis muscle	Same indications than Oberlin's transfer	Valid re-innervation of biceps and brachialis with increased strength in elbow flexion the hand	Possibility of complications in the hand	No experience
The medial cord to MC infraclavicular transfer. **Introduced by Ferraresi and Garozzo in Italy**	Fascicles for the pronator or wrist flexors from the medial part of the medial cord	The whole MC cut at its origin from the lateral cord	Same indications than Oberlin's transfer	Valid re-innervation of both biceps and brachialis at the same time. No need for the medial arm approach	Not possible in those cases of anatomical variants of the lateral cord that branches off for the biceps at the arm level	We routinely use this variant of Oberlin's transfer as it provides a better outcome than the original technique
The brachialis branch to the median nerve transfer. **Introduced by Accioli in Argentina, popularized by Palazzi in Europe**	Branch for the brachialis muscle from the MC	Fascicles for the AIN and FDS in the median nerve	The fascicles for the AIN and FDS are located in the posterior portion of the median nerve The lateral cutaneous nerve of the forearm can be added in the procedure to improve sensitivity in the median nerve territory	Valid re-innervation of finger flexors	Denervation of the brachialis muscle	Limited experience. Favourable outcome
"Somsak's procedure" **The triceps to deltoid nerve transfer.** **Introduced by Somsak Leechavenvongs in Thailand in the 90's, technical variants introduced by McKinnon in USA and Bertelli in Brazil**	Branch to the long head of the triceps in Somsak's technique. In the technical variant introduced by McKinnon, the branch for the medial head	AX	Usually performed via posterior approach Via anterior approach at the axilla in the technical variant by Bertelli	Valid re-innervation of deltoid	Contraindicated when pre-op triceps strength is less than M4: the procedure is usually followed by further decrease of muscle strength	Limited experience. Results less favourable than in the literature

FCU= flexor carpi ulnaris, AIN = anterior interosseous nerve, FDS= flexor digitorum superficialis

Continuous, excruciating pain (deafferentation pain) tortures these patients and disrupts their quality of life (Teixeira et al. 2015; Ciaramitaro et al. 2017). Therefore, in spite of their presumed rarity, the impact of these lesions on the community is relevant as they abruptly change the life of individuals at the beginning or the peak of their productive (professionally and personally) years. In developing countries, these young individuals living with disability become an additional burden to their families already burdened by other social issues.

Micro-reconstructive surgery becomes the only hope to restore function in the affected limb, improving the life of these patients. Early referral for surgical treatment is a prerequisite to obtain a favorable outcome and post-operative daily physiotherapy treatment is also essential. In this paper, the aim is to provide a comprehensive overview on the management and surgical treatment of traction injuries of the brachial plexus. It is beyond the scope of this article to re-analyse the outcome of our surgical series since it was previously published (Garozzo et al. 2013).

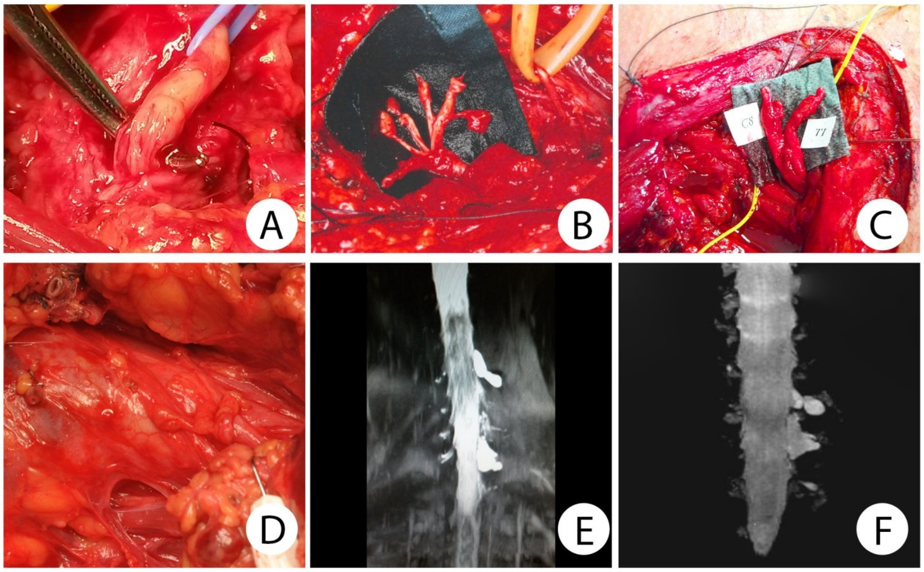


Figure 1: Root avulsions. Avulsions of C5 (A), C8 (B), C8 and T1 (C) and bulky meningocele (D) found at surgical exploration of the supraclavicular brachial plexus. Meningoceles at MRI myelography (E, F)

DIAGNOSTIC ASSESSMENT

Clinical Evaluation

BPIs often occur in multitrauma victims (Narakas 1985; Ferraresi et al. 1994; Midha 1997; Jain et al. 2012; Kaiser et al. 2012; Garozzo et al. 2013; Faglioni et al. 2014; Park et al. 2017) and may easily go unnoticed in the acute stage. In devastating traumas and in comatose patients, a thorough neurological examination can be rather difficult and physicians obviously focus on the life-threatening injuries that require priority in treatment; moreover, BPIs are frequently associated with fractures of the upper limb and functional impairment is often attributed to them.

Therefore the consideration that a brachial plexus injury should be suspected when the following radiological findings and clinical signs are present:

i. Abnormalities of the radial pulse, haemorrhages and ischemia in the upper limb, hypovolemic shock. Found in up to 28 % of patients (Narakas 1985; Jain et al. 2012; Park et al. 2017), these signs are related to vascular injuries associated with BPIs (mostly in infra-clavicular lesions).

ii. Multiple fractures of the transverse processes or laminae of the cervical vertebrae. They are strongly suggestive that there is a brachial plexus injury and usually associated with root avulsions.

iii. Fractures of the first rib, collar bone (Fig. 2) and scapula (Fig. 3).

iv. Hemi diaphragm elevation (Fig. 4). Detected by chest X-Ray and related to phrenic nerve palsy.

v. Horner's sign (Fig.5). Given their close proximity, a traction injury causing avulsions of the lower roots can damage the stellate ganglion and result in eyelid ptosis and meiosis. Horner's sign usually manifests immediately after the trauma but it can occasionally appear 24-48 hours later. The evaluation of brain computed tomography (CT) scans rules out asymmetrical pupils as a sign of rising intracranial pressure. In Horner's sign pupils react well to light, differently from anisocoria in head injuries.

v. Incomplete Brown Sequard syndrome. Evident in only 2% of cases (Narakas 1985; Garozzo et al. 2013), it is related to the long pathways damage consequent of multiple root avulsions.

Weeks or months after the trauma, the recognition of the brachial palsy becomes straightforward due to the evident functional impairment and muscle atrophy (Fig. 6 and 7). At this stage, we try to estimate the extension and severity of the plexus damage to identify patients requiring surgery. Our main concern is to detect the presence of avulsions that can be suspected whenever we find the following signs and symptoms:

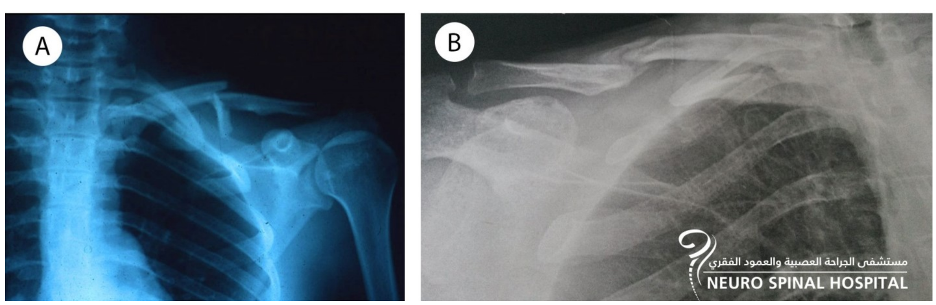


Figure 2: Comminuted clavicular fractures with displacement of bone fractures often cause compression on the underlying brachial plexus thus contributing to the injury (A). Mal-united clavicular fractures (B) may also result in compression on the neural structures.

i. Horner's sign (Fig. 5). It was previously mentioned as related to C8-T1 avulsions. Although it is usually evident even years after the trauma, in a few patients it can regress some weeks or months afterwards.

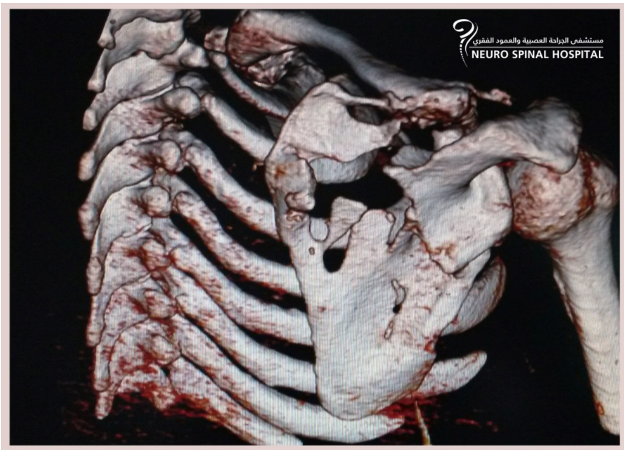


Figure 3: Comminuted fracture of the shoulder blade. Scapular fractures are usually related to severe BPIs: in this case the patient presented multiple root avulsions and an avulsion of the suprascapular nerve from the muscle at the level of the suprascapular notch.

ii. Winging scapula (Fig .7). It is a consequence of a complete denervation of serratus anterior, whose innervation is provided by the long thoracic nerve (LTN), originating from C5, C6 and C7. A residual function can still be present in the muscle even when only one of its 3 roots maintains its continuity with the spinal cord: thus, the evidence of a winging scapula in association with a brachial plexus palsy is a bad prognostic indicator as a complete denervation of the serratus anterior provides indirect evidence of avulsions of the 3 upper roots.

iii. Rhomboid palsy. Rhomboids are innervated by the dorsal scapular nerve, originating from proximal C5: rhomboid denervation occurs in C5 avulsion.

iv. Phrenic nerve palsy (Fig. 4). Is usually well tolerated by the patients and detected by examining the X-Ray of the chest.

v. External pseudo-meningocele (Fig. 8). Is evident in only 3 % of patients (Garozzo et al. 2013).

vi. Hyposthenia in the ipsilateral lower limb. The long pathways damages associated with an incomplete Brown Sequard syndrome usually tend to progressively recover in the weeks or early months after the trauma.

vi. Deafferentation pain. BPIs are often associated with musculoskeletal (consequent to bone injuries) and/or neuropathic pain. Deafferentation pain is a specific form of neuropathic pain consequent to avulsions. Patients usually describe a dull, continuous pain radiating along the upper limb and especially intense on the hand, similar to the sensation of having the extremity crushed inside a vise. Fits perceived as painful electricity can suddenly radiate along the upper limb, with a frequency varying from a few fits per day to 50 per hour. Deafferentation pain is usually worse at night, with cold temperatures, storms or sudden climate changes, after flues or other mild infections, during menstruations in women and even when patients are emotionally unsettled. Its peculiar clinical presentation is unmistakably related to root avulsions, thus representing a bad prognostic indicator.

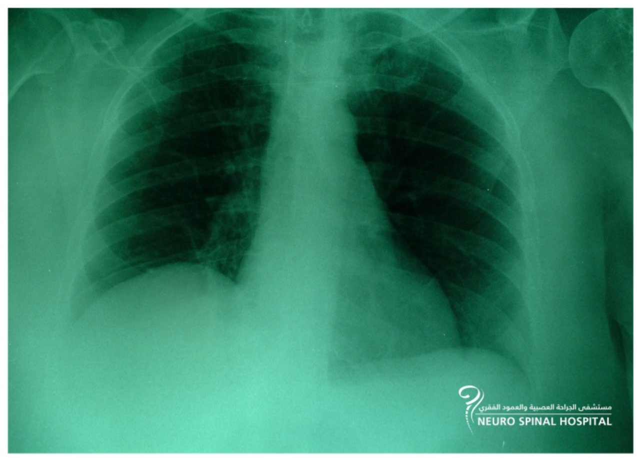


Figure 4: Hemi diaphragmatic palsy

In order to classify the injury pattern, the strength of each muscle innervated by the brachial plexus and its collateral and terminal branches is assessed according to the British Medical Council Score (Medical Research Council Scale 1976) and then recorded on the Merle D'Aubigne diagram (Fig. 9). Sensory loss is also evaluated. Due to overlapping dermatomes, it is considered less reliable than motor function impairment. We always check the elicitation of a supraclavicular Tinel's sign although it can be misleading. In partial avulsions involving only the motor rootlets and with continuity of the sensory rootlets with the spinal cord, Tinel's sign can be present.

Figure 5: Horner's Sign

Figure 6: Severe should atrophy due to complete denervation of spinati and deltoid

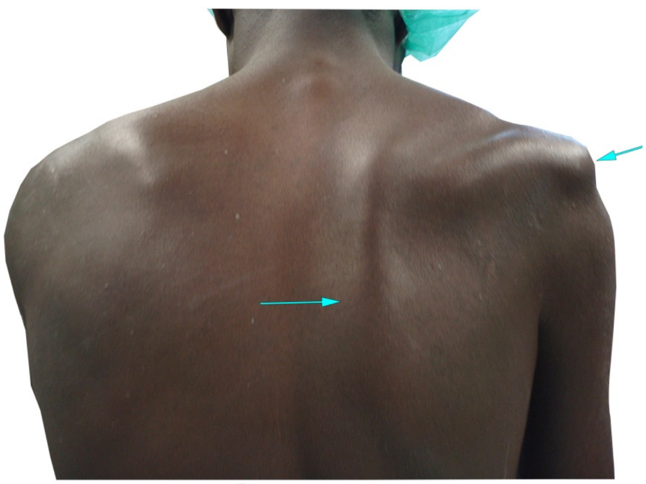


Figure 7: Winging scapula due to complete palsy of serratus anterior in brachial plexus injury with MRI documented C5-T1 avulsions. Note also the remarkable grade of humeral head subluxation.

INVESTIGATIONS

Instrumental assessment hinges on detection of root avulsions by 3 dimensional Magnetic Resonance Imaging (3D MRI). Our MR imaging protocol always includes 3D MR mielography to detect preganglionic injuries (Fig.1E and 1F) and MR neurography (MRN) to evaluate postganglionic lesions. Diffusion Tensor Tractography (DTT) may be an additional modality in the assessment of root avulsions (Gasparotti et al. 1997; Garozzo et al. 2013; Gasparotti et al. 2013). Considering that pseudomeningoceles usually occurs in 3-4 weeks, the patient must be clinically stable, 3D MRI is usually performed one month after the traumatic event to indicate this. Electro diagnostic tests (EDS) are also performed one month after the trauma, as the early electromyography (EMG) cannot distinguish between neuroapraxia and other forms of nerve damage.

Additional investigations are:

i. X-Ray of the chest: to detect possible hemi diaphragmatic palsy.

ii. Angiography: when a vascular lesion is associated with the brachial plexus injury.

iii. MRI of the shoulder: to evaluate the rotator cuff.

iv. 3DCT reconstruction of the scapula: in case of scapular fractures (Fig. 3).

Preoperative Management

Slings and shoulder supporters are advised to prevent or minimize the development of problems caused by the distractive forces consequent to the weight of the denervated upper limb hanging along the body trunk. Wrist and elbow are also at risk but the shoulder joint is the most frequently impaired, and if left unattended, glenoid-humeral subluxation can become quite pronounced (Fig. 5 and 6).

Pain management is also crucial. Medications prescribed are usually Pregabalin, frequently in association with Duloxetine; opiates can be administered. Patients are given indication to start daily physiotherapy treatment as soon as their general clinical conditions allow.

Surgical Treatment

Indication and Timing for Surgical Treatment

When avulsions are demonstrated, surgery is indicated as soon as possible according to the general conditions of the patient. In postganglionic injuries, the patient is followed up, clinically reassessing his neurological condition every month. EDS are repeated every 2 months to detect possible signs of spontaneous re-innervation that are not clinically manifest. When no spontaneous recovery is

Figure 8: Bulky, external meningocele in left brachial plexus injury with C5-T1 avulsions

evident clinically and/or at EMG 4 to 6 months after the injury, indication for surgery is considered.

Surgical Procedural

Surgery is performed under general anaesthesia, no muscular blocks are used. The patient is supine, with his head slightly rotated towards the unaffected side and his shoulder lifted by a pillow in order to adequately expose the supraclavicular area.

The procedure always includes two stages: exploration of the brachial plexus and its micro-reconstruction via anterior approach. In supraclavicular injuries, a complete exploration of the brachial plexus is always performed. In infraclavicular injuries, the supraclavicular plexus is usually not exposed unless there was an associated vascular injury (e.g. a rupture of the subclavian/axillary arteries) that was previously surgically treated. In such cases the supraclavicular area is exposed to obtain adequate control on the subclavian artery before accessing the infraclavicular plexus. Brachial plexus exploration is not performed only in lower plexus injuries after MRI has clearly demonstrated root avulsions (Garozzo et al. 2013; Garozzo 2017).

We use magnification for the entire duration of the procedure. Loupes are used during exploration and nerve sutures are performed under the microscope, with nylon 9-0 and fibrin glue (Tissuecol/Tisseel by Baxter or Evicel by Ethicon).

Concerning intraoperative EDS, only direct neuroelectrical stimulation is used. A thorough intraoperative neurophysiological monitoring is performed only in contralateral C7 (cC7) transfer to minimize the risk of possible complications at the donor site (Garozzo et al. 2013, Garozzo 2017).

Frozen examinations of the root stumps are not used.

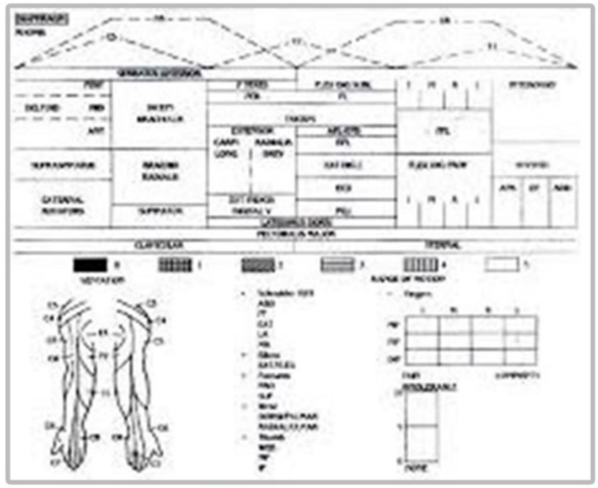
The Repair Strategy Procedures Preferred According to the Injury Pattern

Micro-reconstruction with nerve grafts or nerve transfers is performed according to the information obtained from the neuroradiological investigations and surgical findings. Graft reconstruction can be done when root continuity with the spinal cord is maintained, such as in cases of complete nerve rupture or severe stretch injuries resulting in the formation of neuromas. Sural nerves are usually harvested and used to prepare cable grafts that bridge the two stumps of the nerve whose function must be restored. In cases of complete injuries, we can also harvest the radial sensory branch, medial cutaneous or ulnar nerves.

Graft reconstruction is obviously not indicated in avulsive injuries and nerve transfers are the viable options in such cases: Table 1 and 2 provide an overview of neurotization techniques as per the Author's experience for each nerve transfer. The preferred repair strategies according to each injury pattern are described below.

C5, C6 (C7) Injuries

In upper BPIs, the aim is to re-innervate spinati, deltoid and biceps (Garozzo et al. 2013; Ferraresi et al. 2014; Garozzo 2017). We perform a spinal accessory to suprascapular (XI-SS) nerve transfer to regain spinati muscles. The biceps is re-innervated via the medial cord to musculocutaneous nerve transfer (a variant of Oberlin's technique). The deltoid is restored via thoracodorsal (or subclavius) to axillary nerve transfer or graft reconstruction of the upper trunk (when valid proximal root stumps are available).



NEURO SPINAL HOSPITAL

Figure 9: Merle D'Aubigne diagram for clinical assessment in BPIs.

In the uncommon case of avulsions of the 3 upper roots, spinati and biceps re-innervation are associated with an intercostal nerve (IN) transfer to the LTN to restore serratus anterior (winging scapula regression empowers shoulder stability) and to the axillary nerve to restore deltoid (Garozzo et al. 2013; Garozzo 2017). When a wrist drop is present due to C7 injury, we prefer to perform secondary tendon transfers even if distal nerve transfers (e.g., median nerve to posterior interosseous nerve transfer) have been recently advocated by many surgeons.

C8-T1 Injuries

In lower BPIs, the aim is to regain finger flexion. The brachialis muscle branch of the musculocutaneous to the median nerve transfer is the preferred option to restore finger flexion (Garozzo et al. 2013, Garozzo 2017).

Panplexopathies

In complete injuries, surgery cannot restore the whole function of the upper limb: the reconstruction scheme follows priorities, assuming that elbow flexion and shoulder function (stabilization, abduction and extra rotation) are our primary goals in surgical re-innervation. Elbow extension and restoration of protective sensitivity in the hand are considered secondary goals. At present we consider that valid reinnervation of the hand is basically out of our reach. Regardless of the clinical presentation of a flail arm, four different situations can be distinguished according to the damage suffered by the plexus, each implying a different repair strategy:

i. In 20 % of these patients, some residual activity in the hand flexors spontaneously recovers a few weeks or months after the trauma. When wrist and finger flexors score M3 or plus, we apply a repair strategy similar to that described for upper palsies. However, these injuries are clearly characterized by more severe damage on the plexus than the "pure" upper plexus lesions (Garozzo et al. 2013; Ferraresi et al. 2014, Garozzo 2017)

ii. In more than 50% of total palsies, a viable root stump (usually C5) is found in continuity with the spinal cord (Garozzo et al. 2013). A XI-SS nerve transfer and a graft bridging the root stump to the anterior division of the upper trunk are the basic repair strategy to regain spinati and biceps.

iii. When two root stumps are available, we perform a graft reconstruction of the entire upper trunk. In a second stage, an intercostal nerve transfer to the triceps represents a valid option to implement functional restoration (Garozzo et al. 2013).

iv. In pan avulsions, a XI-SS nerve transfer for the spinati is usually associated with the harvest of 4 intercostal nerves from T3 to T6. T3 is co-oapted to the LTN to reinnervate serratus anterior and thus, empower shoulder stability. The motor branches of the T4-T6 intercostal nerves are connected to the musculocutaneous nerve and their corresponding sensory branches to the lateral root (branching off the lateral cord) of the median nerve in order to restore elbow flexion and regain some sensory function in the hand (Garozzo et al. 2013; Garozzo 2017).

When intercostal nerve transfer is not possible (e.g. multiple rib fractures and/or a cervical spinal injury or a Brown Sequard syndrome consequent to multiple avulsions), cC7 is the only option although this surgical scenario clearly offers further limitations (see Table 1). If the aim is to attempt hand reinnervation, cC7 and/or free gracilis muscle transfer can be considered (Garozzo et al. 2013; Garozzo 2017)

Infraclavicular Injuries

In infraclavicular palsies, surgical exploration offers different scenarios depending on the cords damaged by the lesion and the possible association with a vascular injury (usually previously treated in emergency by vascular surgeons). We mostly perform graft reconstructions according to the surgical findings.

Postoperative Care

The operated limb is immobilized for 2 weeks and the patient resumes physiotherapy afterwards.

DISCUSSION

An Italian orthopedic surgeon, Bonola reported the occurrence of BPIs mainly due to motorcycle accidents (Bonola 1936). Even presently this type of road traffic accident remains the main cause of BPIs (Narakas 1985; Ferraresi et al. 1994; Midha 1997; Jain et al. 2012; Kaiser et al. 2012; Garozzo et al. 2013; Faglioni et al. 2014, Teixeira 2015; Garozzo 2017; Park et al. 2017,) resulting in the reason young males predominate in surgical series. However, due to the cultural transformation of our societies (now more women ride motorbikes), a progressive change in the male/female ratio is observed: in our series, female patients were less than 3% in 2007 and raised to 6% in 2013 (Garozzo et al. 2013).

According to a report, a speed of 47 km/h (29 mph) is enough to cause a brachial plexus injury (Jain et al. 2012). The right side is more affected than the left one, yet the side of the road used for driving does not influence the side of the injury (Jain et al. 2012). Associated injuries are often present in these patients (Narakas 1985; Midha 1997; Jain et al. 2012; Kaiser et al. 2012; Garozzo et al. 2013; Faglioni et al. 2014; Garozzo 2017; Park et al. 2017).

No series concerning African patients is available but there are remarkable differences between Asian and Western patients, likely to be a consequence of the higher velocity of the vehicles in Europe and the USA (Jain et al. 2012). Western patients present more severe BPIs than their Asian counterpart and this is clearly demonstrated by the higher incidence of associated injuries in the former group.

Vascular injuries in BPIs seem to occur in 20-28% of Western patients and in less than 5% of Indian patients (Narakas 1985; Jain et al. 2012). Concerning bone injuries, clavicular fractures occur in 20% of Western patients and 11% of Asian patients (Narakas 1985; Jain et al. 2012; Park et al. 2017). Although traction always remains the main causative mechanism, compression by displaced clavicular bone fragments can also contribute to the brachial plexus damage (Fig. 2). It is reported that 1% of BPIs are exclusively consequent to compression by displaced bone fragments (Della Santa et al. 1991). In such cases, conservative management prevents the recovery of the palsy: thus surgical realignment of clavicular fractures associated with bone fragment displacement should be strongly advocated.

Scapular fractures are usually related to more severe injuries (Kaiser et al. 2012) and in our experience: we often found irreparable injuries of the suprascapular nerve (e.g. avulsion of the nerve from the muscles) in association with comminuted scapular fractures (Fig. 2). Associated injuries delay diagnosis and deeply impact the management of BPIs, timing for surgery, repair strategy and outcome.

In multitrauma victims, diagnostic assessment and surgery for BPIs are obviously taken in consideration only when the life-threatening injuries are solved. For instance, in cases of severe head injuries and prolonged comatose state, indication for brachial plexus micro reconstruction is given only after restoration of a normal state of consciousness. In addition to delaying the surgical timing, severe head injuries also influence the repair strategy and its outcome. Neurotizations require a good brain plasticity and this subgroup of patients usually presents slower post-surgical innervation and less functionally rewarding outcome in comparison with the general population of BPI patients. We strongly do not recommend performance of a cC7 transfer after severe head injuries. Automatization of the re-innervated limb from the donor limb does not systematically occur and is achieved normally after at least 5 years.

Poor neuroplasticity secondary to severe head injuries increases the failure rate of this procedure. Spinal cord injuries due to vertebral fractures or incomplete Brown Sequard syndrome consequent to multiple avulsions should rule out the possibility to perform intercostal nerve transfers (Garozzo et al. 2013; Garozzo 2017).

More than 70% of BPIs are associated with preganglionic injuries with no chance of spontaneous recovery (Narakas 1985; Ferraresi et al. 1994; Garozzo et al. 2013, Garozzo 2017; Park et al. 2017). Clinical suspicion of avulsive injuries should be raised by the assessing physicians, prompting instrumental diagnosis as soon as possible. In our opinion, the development of new imaging modalities certainly relegates EDS to a marginal role in comparison with the past. Although theoretically EDS can distinguish between neuroapraxic and more severe lesions, this is not reliable in reality. The neurophysiological evaluation of a brachial plexus palsy is very demanding and time-consuming and very few specialists have the necessary expertise to manage these procedures. The information given by such techniques is inferred and not directly demonstrated.

Today BPI diagnostic assessment undoubtedly hinges on imaging. After 1994, the 3D MRI has progressively replaced CT myelography. It is non-invasive technique and can provide a visualization of both the proximal structures and the distal plexus (Gasparotti et al. 1997, Gasparotti et al. 2013). Unfortunately there are a number of disadvantages that have to be mentioned. MRI is not affordable in many countries or is still not widely available in developing countries. A world-wide diffusion of 3D MRI to study BPIs is unlikely under the present circumstances. Paradoxically, the countries with the highest incidence of BPIs are mostly areas where healthcare is less accessible than in the Western world.

In order to become reliable and reproducible, MRI processing should be performed by a Neuroradiologist with many years of experience in the field. In any case it is still not completely reliable presenting about 91% of accuracy in detecting avulsive lesions, partial avulsions are still often underdiagnosed.

Therefore it can be clearly inferred that in panplexual injuries, surgical exploration of the brachial plexus still retains a major role, being the only way to completely assess the extent, level and severity of the injury. Moreover in about 5% of supraclavicular injuries there might also be a distal, infraclavicular rupture of the musculocutaneous or the axillary nerves that would invariably lead to failure in case of supraclavicular graft repair.

Regarding repair strategies, in our opinion direct nerve transfers are undoubtedly the winning strategy in brachial plexus surgery. With our experience as well as in literatures (Midha 2004; Shin 2004; El Gammal et sl. 2002; Garozzo et sl. 2013; Garozzo 2017), they provide a faster and better recovery in comparison with graft repair. They also allow a favorable outcome even in late referral cases.

However they are not completely flawless techniques. A report published by Oberlin and his coworkers warns about the risk of partially impairing the hand function with his double transfer technique (Liverneaux 2006). The transection of the donor nerve may imply the loss of function in its original target muscle, consequently no longer suitable for secondary tendon/muscles transfers (e.g. the latissimus dorsi after resection of the thoracodorsal nerve to restore deltoid) and this must be kept in mind when planning the primary repair.

In the preliminary remark under the introduction, we previously published our surgical series in 2013 (Garozzo et al. 2013): thus it is beyond the scope of this paper to re-analyse our surgical series and its outcome. However we summerize our surgical oucomes according to injury patterns. Among supraclavicular injuries, upper brachial plexus palsies (25% of overall BPIs) have an excellent outcome as currently we are able to restore a valid function in more than 90% of cases. Lower brachial plexus injuries are statistically rare (3% of overall BPIs) but nerve transfers allow favorable post-surgical evolution also in these patients. Unfortunately, in complete palsies (about 50% of overall BPIs), especially with multiple avulsions, brachial plexus surgery cannot restore the whole function of the upper limb and is often “a salvage- like procedure”.

In spite of the initial wave of enthusiasm raised by some reports published by Asian surgeons (Wang et al. 2011, Wang et al. 2013), reinnervation of the distal extremity of the upper limb is still out of our reach (Mathews A. et al 2017). Only a basic function can ultimately be regained and certainly incomparable with the flexible refinement of the normal hand. Concerning infra-clavicular injuries (25% of BPIs), surgical outcome is generally favourable for injuries of the lateral and posterior cord and their outflows. Repair of medial cord and its terminal branches (median and ulnar nerves) are often poor.

Although in this paper we do not aim to illustrate in detail pain management and rehabilitation protocols in BPIs, a few remarks are necessary at the end of this discussion. Deafferentation pain is “the” major issue for our patients that firmly claim that it is more devastating and impacting on their quality of life than the disability itself, therefore pain management should be a major concern when treating patients with BPIs.

Finally, we need to emphasize that regular physiotherapy treatment is crucial for these patients. Correct indication and timing for surgery and an excellent repair strategy are jeopardized by lack of physiotherapy or inappropriate rehabilitation treatment. In order to optimize outcome, physiotherapists should work in close collaboration with the brachial plexus surgeon, especially focusing on the chosen re- innervation targets.

CONCLUSION

A tremendous improvement occurred in brachial plexus surgery during the last decades. Therapeutic nihilism should no longer be accepted and access to surgical treatment should become the way of the future. Successful outcomes depend on early recognition of the severity of the injury with consequent prompt referral to the surgeons and regular physiotherapy sessions.

Acknowledgement
We thank our medical illustrator Nasiba Pardaeva for her outstanding technical assistance and Madge Kruger for reviewing the manuscript.

Conflict of Interest
None declared.

REFERENCES

Bonola, A. (1936) La paralisi del plesso brachiale da trauma di motociclette. Chirurgia degli Organi del Movimento. 22:309-313.

Ciaramitaro, P., Padua, L., Devigili, G., Rota E., Tamburin S., Cruccu G. and Truini A. (2017) Prevalence of neuropathic pain in patients with traumatic brachial plexus injury: a multicenter prospective hospital-based study. Pain Medicine. 18(12):2428-2432.

Della Santa D., Narakas A. and Bonnard C. (1991) Late lesions of the brachial plexus after fracture of the clavicle. Annales de Chirurgie de la Main et du Membre Superieur. 10:531-540.

Faglioni, W., Siqueira M.G., Martins R.S., Heise C.O. and Foroni L. (2014) The epidemiology of adult traumatic brachial plexus injuries in a large metropolis. Acta Neurochirurgica. 156:1025-1028.

Ferraresi S., Garozzo, D., Basso, E., Maistrello, L., Lucchin, F. and Di Pasquale P. (2014) The medial cord to musculocutaneous (MCMc) nerve transfer: a new method to reanimate elbow flexion after C5-C6-C7-(C8) avulsive injuries of the brachial plexus: technique and results. Neurosurgical Review. 37:321-329.

Ferraresi, S., Garozzo D., Griffini, C., Resmini, B., Manara O., Foresti, C., Ubiali, E., Bistoni, A. and Ghilandi, I. (1994) Brachial plexus injuries. Guidelines for management: our experience. Italian Journal of Neurological Sciences. 15(6):273-284.

Garozzo D., Basso E., Gasparotti R., Pasquale, P.D., Lucchin, F. and Ferraresi, S. (2013) Brachial plexus injuries in adults: management and repair strategies in our experience. Results from the analysis of 428 supraclavicular palsies. Journal of Neurology and Neurophysiology. 5:170. doi: 10.4172/2155-9562.100 0180.

Garozzo, D. (2017) Traumatic brachial plexus injuries: surgical techniques and strategies. In: Socolovsky, M., Midha R., Rasulic L. and Garozzo D. (eds). Manual of Peripheral Nerve Surgery. From the Basics to Complex Procedures. Stuttgart: Thieme. Pp. 141-147.

Gasparotti, R., Lodoli, G., Meoded, A., Carletti, F., Garozzo, D. and Ferraresi, S. (2013) Feasibility of diffusion tensor tractography of brachial plexus injuries at 1.5 T. Investigative Radiology. l48:104-112.

Gasparotti, R., Pinelli, L., Crispino, M., Pavia, M., Bonetti, M., Garozzo, D., Manara, O. and Chiesa, A. (1997) Three-dimensional MR Myelography of traumatic injuries of the brachial plexus. American Journal of Neuroradiology. 18:1733-1742.

Jain D.K.A., Bhardwaj P., Venkataramani, H. and Sabapahty, S.R (2012) An epidemiological study of traumatic brachial plexus injury patients treated in an Indian center. Indian Journal of Plastic Surgery. 45(3):498-503.

Jupiter, J.B., Leffert, R.D., El-Gammal, T.A. and Fathi, N.A. (2002) Outcomes of surgical treatment of brachial plexus injuries using nerve grafting and nerve transfers. Journal of Reconstructive Microsurgery. 18:7-15.

Kaiser, R., Waldauf, P. and Haninec, P. (2012) Types and severity of operated supraclavicular brachial plexus injuries caused by road traffic accidents. Acta Neurochirurgica (Wien). 154(7):1293-1297.

Liverneaux, P.A., Diaz, L.C., Beaulieu, J.Y., Drand, S. and Oberlin, C. (2006) Preliminary results of double nerve transfer to restore elbow flexion in upper type brachial plexus palsies. Plastic Reconstructive Surgery. 117(3):915-919.

Mathews A., Yang, G., Chang, K.W. and Chung, K.C. (2017) A systematic review of outcomes of contralateral C7 transfers for the treatment of traumatic brachial plexus injury: an international comparison. Journal of Neurosurgery. 126:922-932.

Medical Research Council Scale (1976) Aids to the examination of the peripheral nervous system. Memorandum no 45, London, Her Majesty's Stationary Office.
Midha, R. (1997) Epidemiology of brachial plexus injuries in a multi trauma population. Neurosurgery. 40:1181-1189.
Midha, R. (2004) Nerve transfers for severe brachial plexus injuries: a review. Neurosurgical Focus. 16(5): E5.
Narakas, A.O. (1985) The treatment of brachial plexus injuries. International Orthopaedics. 9(1):29-36.
Park, R.H., Gwang S.L, Kim, I.S. and Chang, J.C. (2017) Brachial plexus injury in adults. The Nerve. 3(1):1-11. [online] Available from: https://doi.org/10.21129/nerve.2017.3.1.1 [Accessed: 30th April 2017].
Shin, A.Y. (2004) Nerve transfers for brachial plexus injuries. Operative Techniques in Orthopedics. 14:199-212.
Teixeira, M.J., Gomez da S., da Paz, M., Bina M.T., Santos, S.N, Raicher, I., Ghalardoni, R., Fernandes, D.T., Yeng, L.T., Baptista, A.F. and Ciampi de Andrade, D. (2015) Neuropathic pain after brachial plexus avulsion - central and peripheral mechanisms. BMC Neurology. 15:73. [online] Available from: https://doi.org/10.1186/s12883-015-0329-x. [Accessed ed., 4th May 2015].
Wang, L., Zhao X., Gao, K., Lao, J. and Gu, Y.D. (2011) Reinnervation of thenar muscles after repair of total brachial plexus alvulsion injury with contralateral C7 root transfer: report of five cases. Microsurgery. 1(31):323-326.
Wang, S.F, Li, P.C., Xue, Y.H., Yiu, H.W., Li, Y.C. and Wang, H.H. (2013) Contralateral C7 nerve transfer with direct coaptation to restore lower trunk function after traumatic brachial plexus avulsion. American Journal of Bone and Joint Surgery. 95:821-827.