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Traumatic brachial plexus injuries: our experience on 485 surgical cases

N.K. Daoutis[1], A.D. Vasileiadis[2], S. Spyridonos[3]

[1]*Consultant Orthopaedic Surgeon, Head of the Department of Hand Surgery & Reconstructive Microsurgery, Athens Metropolitan Hospital*

[2]*Consultant Orthopaedic Surgeon, Department of Hand Surgery & Reconstructive Microsurgery, Athens Metropolitan Hospital*

[3]*Consultant Orthopaedic Surgeon, Head of the Department of Hand Surgery & Reconstructive Microsurgery, Athens Accident Hospital K.A.T.*

ABSTRACT

Traumatic injuries of the brachial plexus tend to, unfortunately, be quite frequent nowadays and often affect young adults. An increase in the number of traffic accidents, especially involving motorcycles, as well as, extreme sports accidents might be correlated to the increase of brachial plexus injuries. Although the research and statistical evidence on this topic is limited, the majority of our cases were involved in one of the two instances.

Initially, the clinician has to make observations in regards to the location of the lesion, the severity of the trauma in order to deduce an expected clinical outcome. The information is accordingly obtained through a detailed history of the accident, a thorough physical examination, as well as, imaging studies and specialised electro-diagnostic and nerve conduction investigations.

Precision in the timing of the surgery, along with the surgeon's knowledge and experience, as well as, the prioritisation of function restoration are of critical importance for the effectiveness of the treatment.

The surgical methods discussed in this article include the following: neurolysis, nerve repair with or without nerve grafts and nerve transfers for the restoration of the impaired functions of the upper limb. Based on our observations, it is important that the surgeon performing the operation is also the one deciding the recommendations for waiting and monitoring the injury.

This article will examine existing research on this subject but will mainly present the 485 cases the authors have treated over the last 25 years. Results will be analysed and discussed in order to present the factors influencing final recovery. It appears that time interval between injury and surgery, as well as, the number of roots involved in the trauma are most crucial.

KEY WORDS: Brachial plexus injury, adult, surgical strategy

CORRESPONDING AUTHOR, GUARANTOR

Antonios Vassiliadis, MD, Orthopaedic Consultant, Department of Hand Surgery & Reconstructive Microsurgery, Metropolitan Hospital, 9 Ethnarchou Makariou street, 185 47, Neo Phaliro, Greece, Tel: +302104809767, Fax: +302104809289, E-mail: anvassiliadis@gmail.com

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Introduction

Brachial plexus is a complex network of nerves, responsible for the motor and sensory innervation of the upper extremity. It is formed in the posterior cervical triangle by the union of the ventral rami of 5th, 6th, 7th, and 8th cervical nerve roots and 1st thoracic nerve root (**figure 1**)

In each spinal segment, roots are formed from the union of the dorsal (sensory) and ventral (motor) rootlets that exit the spinal canal and pass through the corresponding intervertebral foramen.

This composite nerve network can be divided into roots, trunks, divisions, and cords. The roots, trunks, and divisions lie in the posterior triangle of the neck, whereas the cords lie in the axillary fossa. Cords are further divided into the major nerves of the upper extremity [1]

Brachial plexus injury (BPI) is one of the most distressing injuries for the patient. It can effectively impair function in one and sometimes two upper limbs, causing significant loss of motor and sensory function. Patients are, therefore, unable to perform activities of daily living. This, in turn, may lead to unemployment, financial difficulties, depression and in rare instances even suicidal urges [5]

The most commonly observed cases include young males who were involved in a motorcycle accident and were thrown off the vehicle, suffering traction between their neck and shoulder and, thus, damaging the brachial plexus to varying degrees.

It is crucial that these young individuals are treated as early as possible to the best of our ability. This is feasible with the use of modern techniques in microsurgery, provided that the patient is treated in time. Although, there are techniques available for late referrals, commencing the treatment early, makes a significant difference to the outcome.

This article examines the authors' experiences in the management of injuries to the brachial plexus, through the treatment of several cases of adult brachial plexus injuries.

History

One of the earliest descriptions of injuries to the brachial plexus can be found in Homer's Iliad, describing the battle between Hector and Tefcros [2]. However, it was not until this past century that attempts at reconstruction were reported.

The first known documentation of obstetric brachial plexus injury was by Smellie in 1764, who assumed that traction was the cause of the palsy [3].

The introduction of microsurgical techniques, micro-sutures and new developments in nerve repair and regeneration started a revival in the surgical repair of brachial plexus injuries led by pioneers like Narakas, Millesi, Allieu, Brunelli, Gu, Terzis, Doi, and others.[4,6,7,8,9]

Mechanism of Injury

Brachial plexus injuries most commonly affect the supraclavicular zone, while infraclavicular and retroclavicular lesions are less common [10].

It is more common to find the injury at the level of the roots and trunks than in the cords and terminal branches. Two level injuries may also occur and should be taken into consideration for a differential diagnosis. Avulsion injuries at the level of supraclavicular region are observed after violent lateral head and neck turn away from the ipsilateral shoulder, resulting in disruptions within the C_5, C_6, and C_7 roots or the upper trunk (**figure 2**)

According to the majority of the reports [9], 70% to 75% of traumatic brachial plexus injuries are located in the supraclavicular region. 75% of them involve total plexus lesions (C_5-T_1), C_5-C_6 root injuries account for 20–25% of traumatic BPIs, whereas isolated lesions of the lower roots (C_8-T_1) account for 2–3.5% of traumatic BPIs. Total brachial plexus injuries usually involve rupture of C_5-C_6 roots and avulsion of C_7-T_1 roots.

Based on our findings, BP injuries are divided into the following two main categories:

Total Damage : Refers to complete motor and sensory paralysis of the upper extremity, (with Horner sign positive). This was observed approximatively in 60% of all our patients (485). The investigation during surgery revealed avulsions of all the roots (C_5, C_6, C_7, C_8, Th_1) from the spinal cord.

Partial Damage: 40% of all patients (485) that were operated on, fall under this category. Avulsion or disruption relates to C_5 root only (3 cases), in 171 cases there was an avulsion and/or disruption of C_5 and C_6, whereas in 12 cases, avulsion and/or disruption of

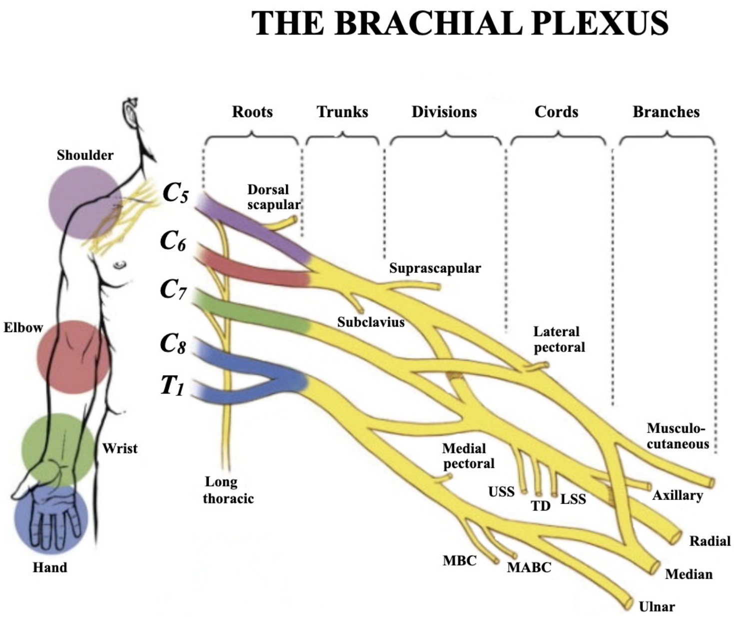

Figure 1: Anatomy of the brachial plexus.

$C_{5,6,7}$ was found, with the function of the lower roots (C_8 and Th_1) intact, therefore, maintaining the ability to fully move the hand.

Even though, open brachial plexus injuries were also observed (6 cases), they were much less common compared to closed BPIs. Lastly, iatrogenic lesions of the brachial plexus were reported (2 cases) during surgical procedures, including resection of the first rib, and carotid-subclavian bypass operations.

Diagnostic investigations

Imaging studies

Currently, plain X-ray films, computed tomography (CT) myelography, and magnetic resonance imaging (MRI) are being used as the main diagnostic tools.

Raised hemidiaphragm on plain X-ray films of the chest is suggestive of phrenic nerve injury.

The presence of pseudomeningocele on myelography indicates a root avulsion injury [11].

MRI provides general information about various components of the brachial plexus.

MR myelography is gradually replacing CT myelography in the diagnosis of root avulsions. However, false-positive pseudomeningoceles have been found in patients with intact rootlets, and false-negative results have been reported during surgical exploration.

Magnetic resonance neurography is a valuable tool in defining peripheral nerve anatomy and brachial plexus. Recently introduced high-resolution 3T MR neurography with three-dimensional imaging [12] is capable of illustrating the condition of nerve roots (avulsions or ruptures), defining the location and extent of injury in the distal part of plexus, as well as the regional denervation muscle changes. An abnormal enhancement of paraspinal muscles indirectly indicates a root avulsion injury.

Electrodiagnostic studies

Electrodiagnostic studies, are of upmost importance in the diagnosis and treatment of brachial plexus injuries [9], when there is good communication between the surgeon and the neuropathologist.

A normal muscle is silent at rest and active during contraction on insertion of electromyography (EMG) needles. Positive sharp waves and fibrillations indicate a denervated muscle, when the test is performed 2-4 weeks post-injury. Polyphasic low amplitude tracings are signs of reinnervation. An electromyographic evaluation of paraspinal muscles can differentiate root avulsions from root ruptures. Furthermore, fibrillation

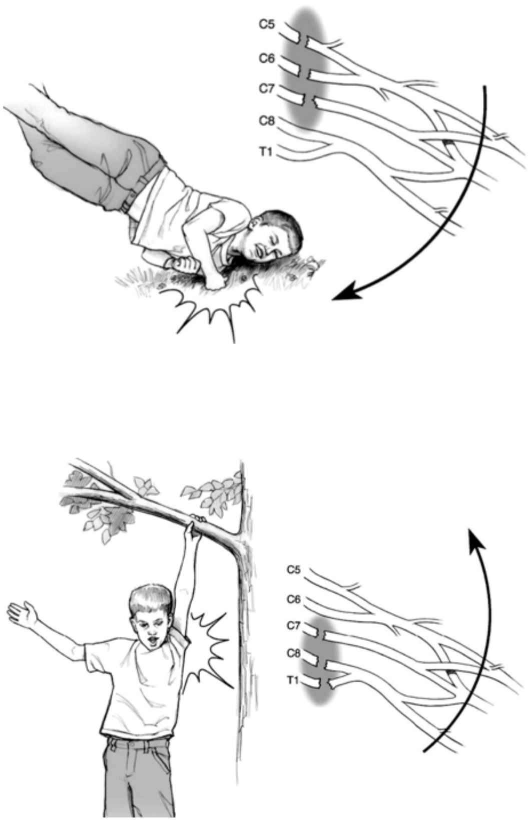

figure 2: *Injury of the upper roots of the B.P. are due to violent lateral head and neck turn away from the ipsilateral shoulder whereas lower roots are injured when there is a forced abduction of the shoulder way beyond 90o.*

potentials and positive sharp waves which are present in axonotmesis and neurotmesis are absent in neuropraxia injuries.

Microsurgical Reconstruction of Brachial Plexus Injuries

<u>Timing of Surgical Procedure:</u> The most critical point while planning a surgical procedure in brachial plexus injuries is the time passed between the accident and the intervention.

Instances which may require an emergency operative procedure include a vascular injury, open penetrating injuries at the level of posterior neck triangle (glass-knife), and open infected crushing/stretching wounds.

Treatment includes prompt restoration of the vessels as well (subclavian artery and/or vein).

An almost immediate surgical operation is, in turn, recommended within the first or second week for complete traumatic palsy of the C_5-T_1 root [5,13].

An early repair refers to the surgery performed within 8-12 weeks after the injury. The indications include a flail limb with severe deafferentation pain, the presence of pseudomeningoceles on magnetic resonance (MR) myelography, a positive Horner's sign, and a rapidly installed muscular atrophy.

In traumatic palsies with no clinical signs or electromyography data of functional recovery surgery is recommended after 3 months from the accident.

Perioperative assessment of the lesion is more accurate after Wallerian degeneration has occurred. Lesions related to iatrogenic aetiology should be surgically explored at an earlier stage, especially when electromyography reveals complete denervation with no signs of functional recovery

<u>Operative techniques:</u> The surgical treatment of BP injuries consists of the following: neurolysis in cases of fibrosis after a 1st degree injury, direct nerve repair in cases of direct injuries, bridging via nerve grafts in

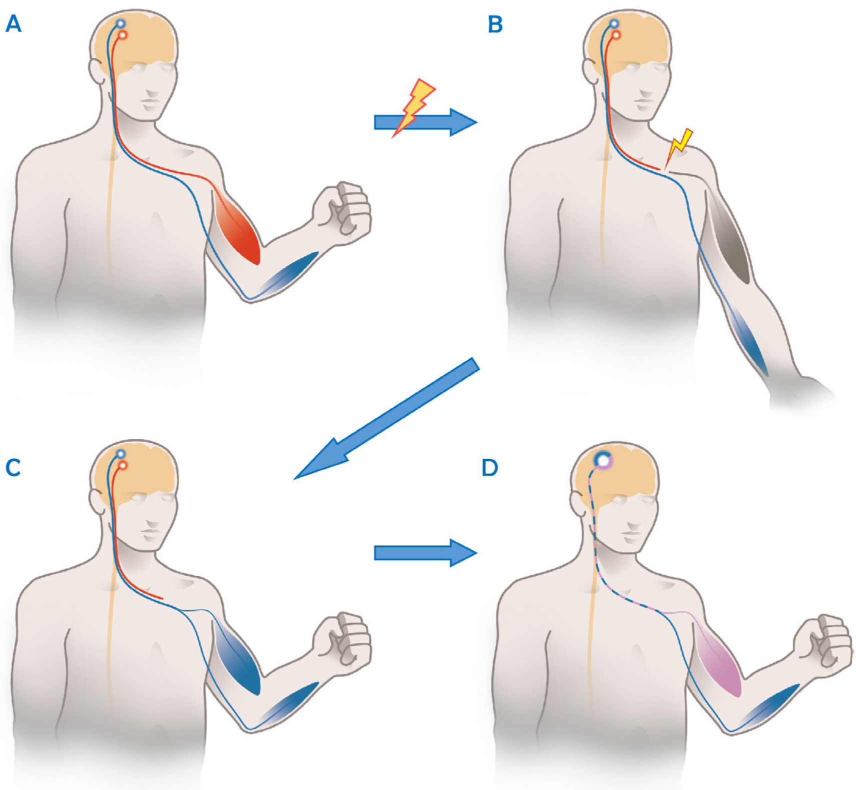

Figure 3: *After an injury of the musculocutaneous nerve, the biceps muscle cannot be activated, while the uninjured ulnar nerve still functions. After the Oberlin's nerve transfer and re-innervation, fascicles of the ulnar nerve control the biceps muscles as well as all other muscles anatomically innervated by the ulnar nerve. Before cortical reorganisation occurs, both muscles are activated together as there is no cortical separation between these nerve fibers. With rehabilitation, the patient learns to use certain cortical axons for "normal" ulnar nerve functions, while others are now controlling the biceps muscle. This allows independent movement of both muscle groups.*

cases of nerve disruption, or neurotisation in cases of nerve or root avulsion.

Neurolysis is performed if an intraoperative nerve action potential (NAP) indicates regeneration. External neurolysis is carried out using a scalpel blade or Metzenbaum scissors. Nerve segments are freed circumferentially and in a proximal and distal direction from either side of the injured segment towards the centre of the damage.

If fascicular structure is found, but there is a large inter-neural gap, an end-to-end repair is not possible. An interfascicular repair is carried out by using sural nerve autografts.

A split-repair is performed when a portion of the element's cross-section exhibits more damage than the remainder of the element. The damaged segment is split away from the segment with more normal appearance and if no NAP is recorded across this damaged segment after it is split away, it is resected and repaired by graft. Excess scar tissue is removed from the segment to be spared, with care taken to not sacrifice the fascicular structure.

Neurorraphy : An end-to-end neurorraphy of the plexus branches is rare, and is used on clear lesions caused by glass or knife.

Among all our patients, this method was applied in 8 cases (6 lesions by knife/glass and 2 iatrogenic lesions).

Nerve Grafting : Nerve grafting is used in cases of disruption of nerve branches and in cases where there is a remaining stump of an avulsed root (6).

For a more precise direction of the axons from the proximal stump to the distal targets (neuromuscular junction, sensory particles), it is preferred to bridge the

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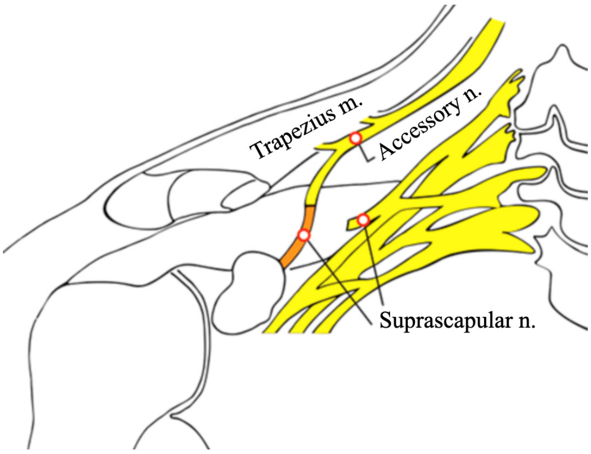

Figure 4: The distal branch of the accessory nerve is transferred to the distal stump of the suprascapular nerve.

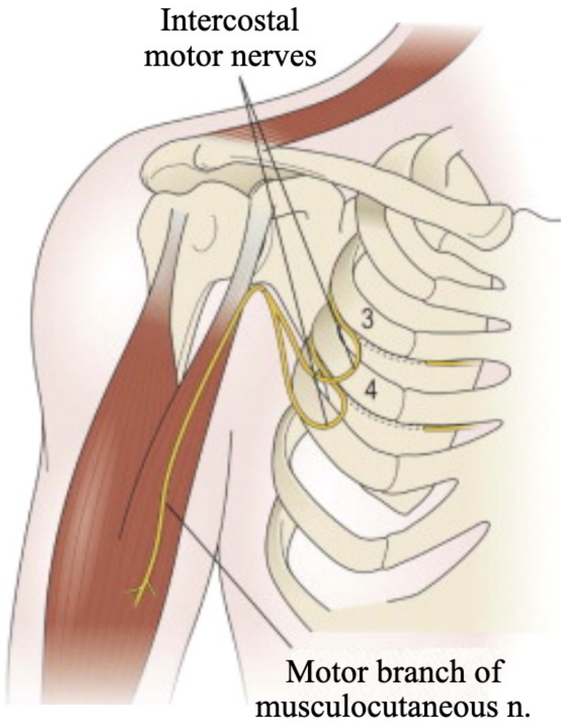

Figure 5: Two motor intercostal nerves are used to reinnervate the motor branch of the musculocutaneous nerve for the biceps muscle.

central stumps with peripheral nerves (musculocutaneous nerve, suprascapular nerve, axillary nerve, medial nerve). In this way, a misalignment of the axons can be avoided. The nerves which can be used as nerve grafts are the following: the gastrocnemius (sural) nerve, the saphenous nerve, the medial cutaneous nerve of forearm, and the superficial radial nerve.

Neurotisation: In brachial plexus injuries, extraplexal nerves such as the spinal accessory nerve, the phrenic nerve, rami of the cervical plexus, or intercostal nerves may be coapted to trunks, cords or nerves the surgeon considers critical for reinnervation Likewise, intraplexal nerves such as a group of fascicles from the ulnar nerve or the posterior cord (in cases of upper plexus injuries of the brachial plexus) can be used for the reinnervation of more important targets. A selective nerve transfer provides restoration of the motor function after a nerve injury, when recovery by the use of neurolysis, nerve repair, or nerve grafting cannot be expected.

Nerve transfers are indicated in avulsion injuries, when there is unavailability of an intact root as well as in cases of delayed reconstruction.

For a healthy individual, activity in the motor cortex of the central nervous system is clearly separated for every nerve [14]. As shown in the picture 3, there are two distinct areas on the cortex, each one corresponding to the ulnar and musculocutaneous nerve respectively. After an injury to the musculocutaneous nerve, there is no activity of the biceps muscle, while the ulnar nerve still functions.

After the Oberlin's nerve transfer and the reinnervation, the cortical territory responsible for the function of the ulnar nerve activates the muscles innervated by the ulnar nerve and, at the same time, the biceps (figure 3). With successful rehabilitation and reeducation the patient learns to use certain cortical axons for the physiological ulnar nerve functions and at the same time others for the function of the biceps muscle [15].

Techniques in Avulsion Injuries on All Roots (C_5 - Th_1)

Motor and sensory paralysis of the entire upper extremity is challenging to treat. It is difficult to regenerate all the upper extremity muscle groups, given the absence of nerve donors, both cranial and spinal as well as the considerable distance between the donor site and the target organ.

Available nerve sources that have not been affected

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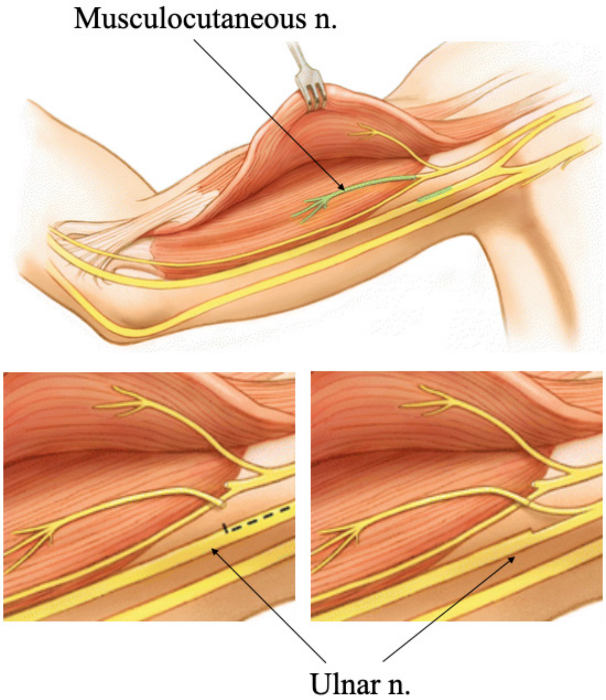

Figure 6: *Transfer of one fascicle (or a group of two fascicles) of the ulnar nerve to the motor branch of the musculocutaneous nerve for the biceps muscle.*

by the injury are the accessory nerve (distal branch), the phrenic nerve, the intercostal nerves, and the motor branches of the cervical plexus.

In a small number of avulsions, the C_5 root is rescued which, because of its large number of myelinated nerve fibers, provides valuable reinnervation to synergistic muscle groups. During the operation, the surgeon can evaluate the appropriateness of the nerve fibers (in conjunction with the anterior and posterior horns of the spinal cord). This is accomplished by stimulating the long thoracic nerve as well as the thoracodorsal nerve and assessing the state of the root (thickness, vascularisation).

The outgrowth of the two branches from the C_5 root is quite proximal inside the foramen, so if there

is a motor response from the respective muscles (serratus anterior, levator scapulae), then the root can be connected with safety with the peripheral nerves, using nerve grafts.

The main goal when it comes to an avulsion of all the roots of the plexus, is the independent movement of the upper extremity, with shoulder stability and abduction, as well as, elbow flexion. For most patients, the lower branch of the accessory nerve (the whole trapezius muscle should never be denervated) (**figure 4**) and the phrenic nerve are used as donors.

In cases where one of the two donors is inadequate, then the intercostal nerves (Th4,5,6,7) are used for elbow flexion via nerve grafts (figure 5). Simultaneous use of the phrenic and intercostal nerves is avoided, in order not to affect the involuntary function of expansion of the hemithorax. The use of the phrenic nerve alone has not shown any postoperative problems in regards to respiratory function.

In addition, adequate shoulder abduction with a slight external rotation (subscapularis) can be achieved following the end-to-end suture of the suprascapular nerve.

The lower branch of the accessory via nerve graft is connected to the musculocutaneous nerve and provides reasonable flexion of the elbow, allowing contraction of the biceps under resistance (3+)

When both functions are restored (shoulder abduction - elbow flexion), secondary arthrodesis of the wrist is then recommended. This, in turn, ensures movement of the forearm and wrist as a whole.

Techniques in avulsions of the upper roots ($C_{5,6,7}$)

In this particular form of injury of the brachial plexus, there is normal function of the hand thus, shifting the focus on shoulder-elbow neurotisation.

These cases are considered excellent in terms of prognosis, given the clinical findings following successful neurotisations within our Department.

So in cases of isolated C_5 avulsion, we carry out the neurotisation that will achieve shoulder abduction and external rotation (supraspinatus, deltoid, teres minor).

The phrenic nerve is connected by end-to-end suture to the suprascapular nerve.

Two bundles from the posterior cord are connected end-to-end to the axillary nerve.

If the injury also affects the A6 root then, elbow flexion is impossible (or difficult) to achieve.

In this case (C5, C6), through a distal incision up to the middle of the arm (picture 6) two bundles of the ulnar nerve (intraoperative motor control) are connected end-to-end to the motor branch of the musculocutane-

METHOD	No of patients	Supraspinatous	Biceps
SUPRASPINATOUS/BICEPS NEUROTISATION		M3 - M4	M3 - M4
Accessory	78	62	-
Phrenic	80	70	1
Ulnar	86	-	82

Table1: Reconstruction of shoulder abduction and elbow flexion through neurotisation of suprascapular and musculocutaneous nerves, from accessory, phrenic and ulnar nerves.

METHOD	No of patients	Receptors	M3 - M4
PLEXO-PLEXAL NEUROTISATION			
C5	22	Suprascapular	19
C5	34	Axillary	25
C5	26	Musculocutaneous	17
C5	8	Lateral cord	5
Posterior cord	26	Axillary	25
C7 (branch to triceps)	4	Suprascapular/ Axillary	4

Table 2: Table1: Reconstruction of shoulder abduction through neurotisation of suprascapular

The results from the remaining number of cases are still being examined and therefore, have not yielded conclusive evidence. However, a rough estimate indicates that their results are in accordance with the existing findings.

ous nerve (figure 6).

The distance of reinnervation is short (3-4 cm) and movement/response in the biceps is observed in the 5th month.

Avulsion of the C_7 root, which was observed in a few cases among our patients, was treated with tendon transfers (sublimis finger flexors, wrist flexors).

This group of patients with avulsion of upper trunks, when applying the aforementioned techniques, displayed an almost full shoulder-elbow reinnervation with a grade of (3+ - 4).

In 4 cases out of 184 upper type avulsions, the score was reduced to 3. In those cases, however, we were not able to control the cause of reduced nerve regeneration. Considering the complete intraoperative evaluation of donor nerves, the most likely cause would be some mechanical involvement of scar - connective tissue formation within the connections.

Post-operative management

Following surgery, the focus is to protect the nerve coaptation, reduce the oedema, and control the pain. Hence, careful attention is required and appropriate wound dressing is necessary. Initially, a bulky dressing is applied in order to protect the area of the nerve repair. The patient is advised to move only the joints not immobilised by the dressing. There is always a risk of applying external pressure to the wound that might cause a disruption at the level of the nerve or nerve graft coaptation. It might be difficult to detect such a disruption given the fact that it is a closed wound and the final result might be affected. It is the surgeon's responsibility, and not the nurse's, to ensure the upper limb stays properly immobilised. A nerve repair is typically immobilised for up to 3 weeks, compared to nerve transfers or grafts. Those are, in turn, performed with laxity so, the immobilisation is less rigid and

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shorter in duration (typically 7–10 days). Nevertheless, we tend to maintain strict immobilisation for 3 weeks, in order to enable the proper healing of the nerve connections.

After 3 weeks, passive motion of the joints is initiated, while the nerve regeneration process is monitored monthly.

As soon as contractions of the restored muscles are observed, intensive physiotherapy with the use of exercises under resistance is recommended.

Systematic and long-term exercise plays an integral part in eliminating muscle atrophy and providing the desired cosmetic result.

Results

During a preliminary study of the first patients, we examined the outcome of 363 nerve transfers for avulsion injuries of the upper plexus. The patients were all males, with a mean age of 24 years (range = 19-40 years). Within the total number of nerve transfer cases (363), 251 were performed for shoulder abduction restoration and 112 for restoration of elbow flexion. An associated vascular injury was encountered in 12 cases. No perioperative complications were encountered. Muscle strength of the affected limb was checked preoperatively and was then reassessed every 2 months.

The last follow-up was after 3 years. The function/strength of the muscle was recorded on a 0 to 5 scale (with 0 indicating no muscle contraction and 5 indicating normal power). From 78 cases of accessory nerve transfer, 62 cases (79,5%) showed an improvement of supraspinatus muscle strength of M3-M4. From 79 cases of phrenic nerve transfer, 70 cases (88,6%) indicated an improvement of supraspinatus muscle straight of M3-M4. In one case, the phrenic nerve was transferred to the musculocutaneous nerve with nerve graft interposition. Postoperative assessment at 2 years showed improvement of the biceps muscle strength of M2, while at 3 years, muscle strength improved to M3+.

From 86 cases of ulnar nerve transfer to the musculocutaneous nerve (Oberlin's transfer), in order to restore elbow flexion, 82 cases (95,3%) showed excellent functional recovery of the biceps muscle (M3-M4). In 3 cases assessment showed an improvement of M2-3, while in one case no improvement was observed. (**Table 1**)

From 22 cases of C_5 transfer to the suprascapular nerve, 19 (86,4%) showed excellent result, from 34 cases of C_5 transfer to the axillary nerve 25 cases (73,5%) were evaluated as excellent, from 8 cases of C_5 transfer to the lateral cord 5 cases were evaluated as excellent, while 17 out of 26 cases of C_5 transfer to the musculocutaneous nerve had a score of M3-M4. The use of a group fascicle of the posterior cord and of a branch of C_7 for the reinnervation of suprascapular and axillary nerve proved to be an very good choice with 25 out of 26 (96%) and 4 out of 4 (100%) respectively resulting in a muscle strength of M3-M4 of supraspinatus and deltoid muscles (**Table 2**).

Conclusions

Amongst the patients that have been operated on within our department, avulsions were the most common injuries, usually caused by high acceleration accidents (fall during a motorcycle accident).

Immediate surgical treatment of BP injuries is recommended only in cases of open wounds of the posterior cervical triangle, with a clear cut of the nerves.

In open injuries that that are associated with vascular damage (subclavian artery or vein), the repairing of the nerve can be postponed, since the vascular repair is the first priority.

In cases of extensive damage and when there are possible avulsions, clinical evaluation is needed, taking into consideration the patient's history, combined with electrophysiological examinations and imaging techniques. This can prevent an unnecessary surgery or delayed treatment that might have serious effects on the functional outcome.

The surgeon performing the potential microsurgical treatment should also be the one providing the recommendations for the waiting time and monitoring the injury. Unnecessary delays due to the long term nature of the results, might lead to defective muscle function or inconsistencies with the surgery.

Given the tight timeframe that muscles need to regenerate, the time between injury and its surgical treatment is valuable.

During surgery, the proximal nerve branches need to be thoroughly assessed with the use of electro-stimulation, since they act as donors for neurotisation. The possible involvement of these nerves in the in-

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jury should also be noted in order to avoid using a damaged donor, which would lead to an ineffective reinnervation. The evaluation of the suitability of a nerve root and whether it can be used as a donor is dependant on the surgeon's experience. The length of the nerve graft does not appear to have an effect on the regeneration, however, if possible, an end-to-end connection between the donor and peripheral nerve is preferred.

The postoperative course should be monitored regularly by the surgeon himself or an experienced member of the team (once a month). Before the target muscle is restored, the patient is encouraged to passively mobilise the joints. Intensive physiotherapy for the muscles with the use of resistance, significantly improves muscle strength. The regained function can further be improved in cases that allow for palliative surgery.

After 18 months the final result can then be evaluated.

To conclude a significant amount of our cases indicated an overall improvement after surgery, with an estimated 75% showing successful reinnervation of the paralysed muscles.

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