BRACHIAL PLEXUS INJURIES – REVIEW OF THE ANATOMY AND THE TREATMENT OPTIONS

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ABSTRACT

Brachial plexus injuries are still challenging for every surgeon taking part in treating patients with BPI. Injuries of the brachial plexus can be divided into injuries of the upper trunk, extended upper trunk, injuries of the lower trunk and swinging hand where all of the roots are involved in this type of the injury. Brachial plexus can be divided in five anatomical sections from its roots to its terminal branches: roots, trunks, division, cords and terminal branches. Brachial plexus ends up as five terminal branches, responsible for upper limb innervation, musculocutaneous, median nerve, axillary nerve, radial and ulnar nerve. According to the findings from the preoperative investigation combined with clinically found functional deficit, the type of BPI will be confirmed and that is going to determine which surgical procedure, from variety of them (neurolysis, nerve graft, neurotization, arthrodesis, tendon transfer, free muscle transfer, bionic reconstruction) is appropriate for treating the patient.

Keywords: BPI; brachial plexus injuries; anatomy of brachial plexus, treatment options for brachial plexus injuries, bionic reconstruction

1. INTRODUCTION

Brachial plexus injuries are still challenging for every surgeon taking part in treating the patient with BPI, needing to know the complex anatomy providing function of the upper limb and possible treatment options that will do the best in restoring the function of the upper limb. It can be seen as a complex network of nerve fibers, arising from anterior branches of the lower four cervical spinal nerves (C5-C8) and the first thoracic spinal nerve (T1) [1, 2]. The upper limb, part of the upper thoracic wall and part of the cervical structures are innervated by the bra-

chial plexus. The anatomical position makes it vulnerable during trauma, and also very often during childbirth [3, 4]. Using motorcycles as a transport more often in the last years have been the reason for increasing the number of brachial plexus injuries [5, 6]. BPI can be divided into injuries of the upper trunk (Erb-Duchene C5/C6), extended upper trunk (Erb-Duchene C5, C6, C7), injuries of the lower trunk (Dejerine-Klumpke C8/T1) and swinging hand where all of the roots are involved in this type of the injury. If the upper trunk is injured only, the prognosis is better

compared to the isolated trauma of the divisions, upper roots or the lower trunk [7]. Starting from the 1940s and 1950s with more serious approach to the treatment of this kind of injuries, from Seddon [8] and Bateman [9], different type of operative procedures were involved in the treatment, including amputation or arthrodesis of the shoulder, elbow or the wrist, depending from the level of injury. In the 1963 again Seddon [10] proposed nerve graft as a surgical option when there is a loss of the nerve segment, instead of the drawing together upper and lower part of the nerve, and keeping the patient in unnatural position or even shortening the collar bone. Five or six months after the injury it was considered to wait before indicating the injury, in the 1990s, but the development of more precise imaging diagnostic methods and electrical studies indicate surgery to be done earlier than more of three months, because of the better prognosis of the nerve regeneration [11]. Suturing intact nerve to the injured one, known as a technique of neurotization, have boost the results after brachial plexus surgery.

2. ANATOMY OF THE BRACHIAL PLEXUS

Brachial plexus can be divided in five anatomical section from its roots to its terminal branches. All of the spinal nerves have anterior root (radix ventralis) that provide motor nerve fibers and posterior root (radix dorsalis) that provide sensitive nerve fibers. When this two roots merge, the spinal nerve is formed but shortly after, in the intervertebral aperture it gives 4 branches, from which anterior is the thicker one that take roll in forming of the brachial plexus. Roots of the brachial plexus are the anterior branches of the lower four cervical spinal nerves (C5-C8) and first thoracic spinal nerve (T1) in most of the cases [12, 13], but there are also some anatomical variation that include anterior branches from C4 to C5 (that is known as a prefixed plexus brachialis) and anterior branches from T2 to T1 (also known as post fixed brachial plexus). The first three roots arise above the vertebral body while the last two exits below their numbered vertebral body. The roots give same segmental supply to the prevertebral and scalene muscles just before they form trunks, placed between the middle

and anterior scalene muscles [1, 12, 13]. Going from the upper part distally, three branches divide directly from the roots: the dorsal scapular nerve (have origin from C5), the long thoracic nerve (have contribution from C5, C6 and C7) and the first intercostal nerve that partially arise from T1 root. We need to know that in this level, the phrenic nerve receives some nerve fibers from the brachial plexus, but also gives contribution to it, that can be noticed from changing the thickness of the nerve when it passes C5 root. Brachial plexus trunks are located in the neck region, in the triangle know as the posterior cervical triangle. There are three trunks, upper, middle and lower trunk. The upper trunk is formed by merging the C5 and C6 nerve roots, the middle trunk is an extension of the C7 nerve root and the lower trunk is made from the C8 and T1 nerve roots. At this anatomical section only the upper trunk has lateral branches, subclavian nerve, like anterior branch from upper trunk, and suprascapular nerve that is posterior branch of the same trunk [13], that will be discussed later in our paper with all of the lateral and terminal branches. Roots and trunks according to its anatomical correlation with collar bone are located above its level or in the space know as a supraclavicular space. Posterior to the collar bone each of these three roots divide into two divisions, anterior and posterior with no lateral branches given. Going at the level below the collar bone, beneath pectoralis minor muscle, the division starts to form the posterior, lateral and medial cords. The names of the cords are given according to their position to the axillary artery in its middle portion. The lateral cord lies lateral from it, the posterior is behind this portion, and the medial cord after crossing the axillary artery lies medial to it [13, 14]. The anterior divisions of the upper and middle trunk form the lateral cord, the medial cord is a continuation of the anterior division of the lower trunk and the posterior divisions of all three trunks form posterior cord. Because of this complex network with merging and dividing of the nerve fibers starting from the roots, the three cords have inputs from different levels, and only the posterior cord receives input from all the roots from C5 to T1. The upper subscapular, long thoracic nerve and the lower subscapular nerve are lateral branches from the posterior cord that end up with two terminal branches, radial and axillary nerve. C5, C6 and C7 through upper and middle trunk anterior divisions, give input to the

lateral cord. From the lateral cord there is only one lateral branch, lateral pectoral nerve, and then it ends up or terminates giving up lateral root for median nerve and one of the terminal branch, musculocutaneous nerve. The anterior division of the lower trunk that is formed by C8 and T1 nerve roots, continues in the medial cord, so the lateral and terminal branches from this cord have input from C8 and T1 respectively. Arising from this medial cord we have three lateral branches, medial pectoral nerve, medial cutaneous nerve of the arm and medial cutaneous nerve of the forearm. The medial cord terminates in the ulnar nerve and the medial root of the median nerve that unites with its lateral root [12, 13, 14].

2.1 Nerves arising from brachial plexus

2.1.1 Lateral branches

Dorsal scapular nerve, long thoracic nerve and the first intercostal nerve are the three branches that arise directly from the nerve roots. We have mention that C5 nerve root gives nerve fibers that merge with the one from the C3 and C4 nerve root, forming phrenic nerve. Subclavian nerve and suprascapular nerve are lateral branches that give rise from the superior trunk. The lateral pectoral nerve is a branch of the lateral cord, upper subscapular, thoracodorsal and lower subscapular nerve are branches that come from posterior cord, while the medial pectoral nerve, medial cutaneous nerve of the arm and medial cutaneous nerve of the forearm derive from medial cord.

1. Dorsal scapular nerve; 2. Suprascapular nerve; 3. Nerve to subclavius; 4. Lateral pectoral nerve; 5. Musculocutaneous nerve; 6. Axillary nerve; 7. Median nerve; 8. Ulnar nerve; 9. Medial cutaneous nerve of the forearm; 10. Medial cutaneous nerve of the arm; 11. Radial nerve; 12. Lower subscapular nerve; 13. Thoracodorsal nerve; 14. Medial pectoral nerve; 15. Upper subscapular nerve; 16. Long thoracic nerve

Fig. 1. Brachial plexus

Table 1. *Lateral branches of the brachial plexus*

Lateral branches	Roots	Innervation	Function	Clinical deficits
Dorsal scapular nerve (Nervus dorsalis scapulae)	C5	- levator scapulae muscle - minor rhomboideus muscle - major rhomboideus muscle	- Elevate scapula - Pulls the scapula to the midline	Unable to pull the shoulder back and scapula is farther from the midline compared to the uninjured side
Long thoracic nerve (Nervus thoracicus longus)	C5, C6 and C7	serratus anterior muscle	- Keep the scapula close to the posterior wall chest - Helps elevation of the arm and lifting weight overhead and also assist in respiration	Winging of the scapula on the injured side
First intercostal nerve (Nervus intercostalis)	T1	- sensory supply to a small portion of skin in the first intercostal space - motor supply to the first intercostal muscle	Elevating and depressing the rib cage during the process of breathing	
Subclavian nerve (Nervus subclavius)	C5 and C6	subclavian muscle	Take part in elevation of the first rib and depression of the collar bone	
Suprascapular nerve (Nervus suprascapularis)	C5 and C6	- supraspinatus muscle - infraspinatus muscle	- Abduction of the arm, pulls the head of the humerus medial - External rotator of the shoulder	Back pain and problems with abduction and external rotation of the arm
Lateral pectoral nerve (Nervus pectoralis lateralis)	C5, C6 and C7	major pectoral muscle	Flexion of the humerus, adduct the humerus, medial rotation of the humerus and keeping the arm attached to the trunk of the body	Atrophy of the sternal part of pectoral major muscle and limitation of shoulder movement
Upper subscapular nerve (Nervus subscapularis proximalis)	C5 and C6	subscapular muscle	Preventing displacement of the head of the humerus and internally rotates the humerus	Difficulty during internal rotation of the shoulder and stability of the joint
Lower subscapular nerve (Nervus subscapularis distalis)	C5 and C6	- subscapular muscle - lower part - also give motor branches to teres major muscle	adducts, internal rotate shoulder, depresses and abducts scapula.	Difficulty during internal rotation of the shoulder and adduction
Thoracodorsal nerve (Nervus thoracodorsalis)	C6, C7 and C8	latissimus dorsi muscle	external rotation of the trunk but also is responsible for adduction, internal rotation and extension on the shoulder	weakness in shoulder movement
Medial pectoral nerve (Nervus pectoralis medialis)	C8 and T1	pectoral muscles		
Medial cutaneous nerve of the arm (Nervus cutaneus brachii medialis)	C8 and T1	sensory supply skin over the lower medial and posterior part of the arm		
Medial cutaneous nerve of the forearm (Nervus cutaneus antebrachii medialis)	C8 and T1	sensory innervation of the skin over the biceps muscle, on the ulnar side of the forearm from elbow to the wrist		

2.1.2 Terminal branches

Brachial plexus ends up as five terminal branches, responsible for the upper limb inner-

vation, musculocutaneous, median nerve, axillary nerve, radial and ulnar nerve.

Table 2. *Terminal branches of the brachial plexus*

Terminal branches	Roots	Innervation	Function	Clinical deficits
Musculocutaneous (Nervus musculocutaneus) lateral cutaneous nerve of the forearm	C5, C6 and C7	- brachial muscle - coracobrachial muscle - biceps brachii muscle - sensory innervation to the skin of the lateral forearm	- flexion of the elbow - flexes the elbow and adduct the shoulder - flexes the elbow, supinates forearm	- Very weak flexion of the elbow - Weak supination of the forearm
Median nerve (Nervus medianus) recurrent branch and the palmar digital nerves	C5, C6, C7, C8 and T1	- sensory supplying the thenar eminence, lateral 2/3 of the palm of the hand, palmar side of the 3½ fingers and dorsal finger tips of the same fingers - all of the muscles of the anterior compartment of the forearm except FCU and medial two parts of the flexor digitorum profundus. - LOAF muscles (lateral two lumbricals, opponens pollicis, abductor pollicis brevis and flexor pollicis brevis)	- Flexion of the digits - grip strength and thenar eminence	- Numbness of the skin on the median nerve distribution, weak grip strength and wasting of the thenar eminence - Inability to flex the wrist, pronate the forearm, abduct the wrist, flexing the proximal interphalangeal joint of the four finger and distal interphalangeal joint of the forefinger and middle finger (hand of benediction)
Axillary nerve (Nervus axillaris) motor branch for the long head of the triceps brachii [15] lateral cutaneous nerve of the arm	C5 and C6	- deltoid muscle - teres minor muscle	- abduct, flexes and extends shoulder - stabilization and externally rotations of the shoulder - Sensory innervation to the “Sergeant’s patch” over lower part of deltoid muscle	deltoid wasting, weakness of shoulder flexion, extension, exgternal rotation and also profound weakness of shoulder abduction from 15-90 degrees accompanied with numbness over the sergeant’s patch.

Radial nerve (Nervus radialis) superficial branch Deep branch posterior interosseous nerve	C5, C6, C7, C8 and T1	• triceps brachii, brachialis, brachioradialis, anconeus and extensor carpi radialis longus • sensory supply to the dorsum of the hand, thumb and three and a half fingers without nail beds • extensor carpi radialis brevis and supinator muscle • extensor digitorum, extensor digiti minimi, extensor carpi ulnaris, abductor pollicis longus, extensor pollicis brevis, extensor pollicis longus and extensor indicis	• extension of the forearm and hand • sensation of the skin in the lateral arm, back side of the forearm, half of the dorsum of the hand (radial) and the dorsal skin covering the three and a half fingers without their nail beds • extension of the fingers	• wrist drop • supination can be lost or weak • loss of sensation of the skin in the lateral arm, back side of the forearm, half of the dorsum of the hand (radial) and the dorsal skin covering the three and a half fingers without their nail beds. • extension of the fingers will be lost
Ulnar nerve (Nervus ulnaris) digital branches deep branch	C8 and T1	• flexor carpi ulnaris and medial half of deep flexors • palmar branch gives sensor supply to the hypothenar • dorsal branches for sensory innervation of the ulnar side of the hand and upper part of the one and a half fingers • motor supply to the hypothenar muscles (opponens digiti minimi, abductor digiti minimi and flexor digiti minimi brevis) • third and fourth lumbrical muscles, dorsal and palmar interossei muscle, adductor pollicis and the deep head of flexor pollicis brevis	• Flexion of the wrist • Sensation over the hypothenar region • Sensation over ulnar side of the hand and upper part of one and a half finger	• At elbow level - loss of sensation to the ulnar side of the hand and the one and a half finger from volar and dorsal side, accompanied with difficulty in the flexion of the wrist and 4th and 5th finger - claw hand deformity • On the clinical finding will be noticed the weakness of adduction of the thumb. • Damaged ulnar nerve at the level of the wrist represent with loss of sensation only at the ulnar side of the palm and more deformed claw hand deformity. • Adduction of the thumb is also lost.

3. TREATMENT OPTIONS FOR BPI

Low energy penetrating injuries or high energy injuries that lead to amputation of the upper arm are very uncommon, open wounds BPI, seeking for nerve repair quickly after the time of injury, when general health status of the patient allow us. If it is impossible to do the nerve reparation at that time, pain control, starting the process of rehabilitation and evaluating the injury through electromyography, CT myelography or MRI should be done preoperative giving us needed evidence for the type of the injury. In closed wounds type of brachial plexus injuries, surgical treatment might be planed after 3-6 months if there is no sign of functional recovery, with same preoperative preparation. If all of the preoperative findings suggest of eventual preganglionic lesions, the transfer of the nerve is a choice of operative treatment that need to be done.

3.1 Non-surgical treatment

All the patients that do not go under surgical treatment in the moment or early after the trauma, need to start with physical therapy that will strengthen the muscles that are functional and keep range of motion of the upper extremity, otherwise stiffness of the hand is unavoidable. Chronic edema as a result of no movement in the arm muscles and sympathetic denervation led to loss of the vascular tonus, and is decreased by keeping the arm in elastic bandages and raised. Pain, more significant in patient with avulsions of the roots, is managed by using NSAIDs and opioids in the beginning and antiepileptics drugs later, when neuropathic pain occur. If there is no relief of the pain with medications, surgical treatment for destroying the signal transmission should be taken in consideration [16, 17]

3.2 Surgical treatment

According to the findings from the preoperative investigation combined with the clinically found functional deficit, the type of BPI will be confirmed, and that will determine which surgical procedures, from variety of them, is appropriate for treating the patient. The decision for bringing back the stability of the shoulder or flexion of the elbow sometimes have to be made in view of the fact that small amount of nerve units are available.

3.2.1 Neurolysis

As one of the early stages of nerve reconstruction in BPI, neurolysis or releasing the nerve from fibrous tissue, may help in cases with neuroma in continuity if there are enough viable fibers. Nowadays it is possible during surgery, with electrical studies, nerve action potential (NAP), to determine the viable nerve fibers, and to decide whether to do resection of that part of the nerve and then nerve transfer or neurolysis will have satisfactory outcome. But, the clinical outcome of just neurolysis is hard to recognize, because improvement may be result of many other factors.

3.2.2 Nerve graft

Introduced by Seddon, in 1963 [10], the nerve graft technique has been used by many others surgeons, confirming good outcome results in selected BPI [18, 19]. Healthy upper end of the nerve, without axial damage is one of the condition for good outcome, depending also on the length and number of used nerve grafts, and the scar found at the place that can lead to bigger gap between the ends. When there are more nerves injured, prioritization which nerve to be repaired with nerve graft needs to be done, giving the priority on the flexion in the elbow joint, abduction the shoulder and giving sensation of the forearm. Medial cutaneous nerve of the forearm or sensory branch of the ulnar nerve are the usual donor nerves from the arm, but mostly the sural nerve has been used as a nerve donor in addition of the length that can be provided (up to 40 cm). Nerve grafts that are less than 10 cm [18] give better functional results, when they are grafted and in the same time inverted, which will minimize the chance of losing some axial branches. Using the fibrin glue, recently, reduced the need of stitches that made grafting easier and more secure, helping in the aim of achieving the best fixation of the two ends to be tension free [8]. Of course, surgical technique and the experience of the surgeon have a serious input in the final outcome.

3.2.3 Neurotization

The process of neurotization is a procedure in which undamaged motor nerved is transferred to another, injured nerve, and this undamaged nerve can come from the brachial plexus (known as intraplexus transfer), or from

elsewhere (known as extraplexus transfer). Suturing the transferred nerve close to the motor units and not using nerve grafts are improving the final outcome [20, 21, 22]. There are some authors [11, 23] that have indicated the influence of the primary reconstructed brachial plexus injuries, increasing the chance for reinnervation of the antagonist group of muscles.

3.2.3.1 Intraplexus transfer option

There are a few options for intraplexus transfers to be done, described later.

Radial nerve transfer to the axillary nerve, in which branch from the radial nerve is transferred to the injured axillary nerve, posterior branch. With this procedure the clinical outcome seen in a treated patient demonstrated good results with more than 120-degree shoulder abduction. The result is boosted when this procedure is combined with neurotization of the accessory nerve with the suprascapular nerve [24, 25].

Ulnar nerve transfer to musculocutaneous nerve, firstly described in 1994 from Oberlin et al. [26] provides neurotization of the ulnar nerve to the musculocutaneous nerve, motor branch, supplying the biceps and providing excellent results [27, 28]. The best results are seen if the injury was treated six months after the trauma, with worse result in the one treated after more than 12 months after the initial trauma [24]. M3 biceps strength or more have been observed in 94-100% of the patients, and 75-94% of the patients have M4 biceps strength. Oberlin 2 surgical procedure, is a modification, in which fascicle from the median nerve has been used for neurotization of the brachial muscle motor branch. Significant difference in the outcome was not found, comparing Oberlin to Oberlin 2 surgical procedure [29].

Medial pectoral nerve transfer to musculocutaneous nerve is a procedure where the transfer of the medial thoracic nerve is done to the musculocutaneous nerve. This technique was firstly described in 2003 by Brandt and Mackinnon [30], with good functional outcome in the flexion of the elbow. This nerve can also be used not only for neurotization musculocutaneous nerve, but also for axillary, suprascapular and accessory nerve. Using this nerve as a donor remains controversial mostly because of the inappropriate diameter match, limitation in length and loss of the internal rotation of the shoulder joint [31].

3.2.3.2 Extraplexus transfer option

Few options are also available in brachial plexus surgery using extraplexus nerve donor of the root.

Phrenic nerve transfer to musculocutaneous, described for the first time in the 1990, by Gu et al. [32], is not recommended for children younger than two years old, and in patients that have had pre-existing pulmonary diseases, knowing the roll of the phrenic nerve in breathing. In most of the cases of brachial plexus injury, the phrenic nerve is, in general, undamaged and knowing that C3 and C4 spinal nerve gives the biggest contribution to its existing, makes the phrenic nerve a good candidate for donor nerve. The dissection of the phrenic nerve needs to go as lower as possible, giving chance not to have need to use a nerve graft.

Phrenic nerve transfer to suprascapular nerve, is an option that needs to be considered instead of the spinal accessory nerve to suprascapular, giving in advice the short distance to the effector area and shorter period that need to be waited, for the recovery of the function, resulting with good outcomes [32]. This type of neurotization should be avoided if simultaneously nerve transfer from the intercostal nerve has been considered.

Accessory nerve transfer to suprascapular nerve, it is likely the most often used type of nerve transfer, for the reason of the frequency of the suprascapular nerve injuries and the easiness in performing the procedure. Due to the close relation of these two nerves it allows using the same route for exploration of the injuries of the brachial plexus. Shoulder stability achieved with this procedure boost elbow flexion, but provide unsatisfactory external rotation of the shoulder and abduction of 66 degrees in 60% of the patients [22].

Contralateral C7 to the median nerve was described in 1992, by Gu et al. [33], introducing the C7 root from the contralateral side to be harvested and using nerve graft, usually ulnar nerve from the injured side, connected to the median nerve. Numbness of the fingers (thumb, index, and long finger) are usually found on the donor side in the first 3 months from the operation, decreased grip strength but not affecting the pinch strength [34]. Because of the distance between the contralateral C7 root and the recipient nerve, which is about 30 cm, the used nerve graft needs to be vascularised or this procedure to be done in two stages, maintaining the regenerative potential of C7 [35].

Intercostal nerve transfer to musculocutaneous nerve, is a procedure where the intercostal nerve, its motor branch, is transferred to the musculocutaneous nerve. The dissection of the intercostal nerve is as close to the sternal region [36], to provide acceptable length by avoiding using the nerve grafts. The repair of the elbow flexion with this technique provides good results, which can be worsen by these factors: surgical treatment five months after trauma, bad adaptation of the ends, use less than three intercostal nerves, using of the grafts or tension at the suture line and shoulder instability [37].

3.2.4 Arthrodesis

As a procedure, arthrodesis means surgical immobilization of the joints, by fusion of the bones, and these type of surgery was used in the patient with brachial plexus injuries until the 1960s, among other procedures, as external derotation osteotomy, wrist arthrodesis and limb amputations [38]. Intact acromioclavicular, sternoclavicular and scapulothoracic joint need to be present, otherwise it may affect the success of the arthrodesis of the shoulder. Shoulder joint should be fussed in 20 degrees abduction, 30 degrees of internal rotation and flexion, providing independent daily activities of the patient if the motion mobility of the hand is preserved or repaired with nerve transfer or nerve grafts. Wrist arthrodesis, as a complementary procedure, releases the patient from the wrist pain and also gives stability to the hand, helping and improving the performance of the patient daily activities, more superior if double free muscle transfer for hand function was performed [39, 40]. Improvements that have been done in the field of nerve transfers and free muscle transfers have significantly changed the way of the brachial plexus injuries treatment and has made arthrodesis exceptional approach.

3.2.5. Tendon transfer

There are more options for tendon transfers in the surgical treatment of the brachial plexus injuries. A transfer to be successful needs to be done by following the basic principles, but the muscle strength is almost always, at least, one grade lower on the measurement scale.

For maintaining the shoulder stability, plenty of tendon transfer techniques exist [41], but the most used ones are:

The transfer of the trapezium muscle, acromial insertion, to the upper part of the humerus (together with a segment of the acromion) maintaining shoulder abduction, or transfer of the lower parts of the trapezium muscle to the intertuberosus sulcus, using graft from fascia lata or maximal dissection and using aponeurotic tissue, gaining external rotation [42, 43].

The transfer of the latissimus muscle, as another surgical procedure that provides external rotation, was described by L' Episcopo firstly, with modification of this technique later. The surgical procedure consists of transferring the latissimus dorsi tendon insertion from its normal anatomical position, on the front medial side of the humerus to the new position on the lateral and back side, helping the external rotation.

Transfer of the posterior part of the deltoid muscle restoring anterior segment deficit.

Elbow flexion restoration influences, at most, the final functional and clinical result after treatment of the brachial plexus injuries. Stable and mobile elbow, with sufficient flexion strength is crucial for acceptable upper limb function [44]. Restoring good muscle strength and providing a sufficient range of elbow motion is a goal that needs to be achieved with one of the following surgical procedures:

Flexor-pronator muscle transfer for the humerus [45], illustrated for the first time in 1918, by Steindler, consists of transfer of the flexor forearm muscle to a proximal section, metaphyseal region of the humeral bone. The results are better if the bone is fixed closer than 5 cm to the medial epicondyle and the existing elbow flexor musculature has the grade 2, at least, with bad outcome in the total elbow paralysis. C8 and T1 nerve roots need to be undamaged for this technique to achieve success in treating patient.

Greater pectoral muscle transfer to biceps muscle, also known as Clark technique [46], can be used when pectoral muscle innervation is intact, that is unusual knowing the innervation of the pectoral muscle. Shoulder arthrodesis is mandatory, because distal suture of the pectoral muscle to the biceps muscle is not tension free, muscle to muscle suture type.

Latissimus dorsi muscle transfer to the biceps muscle, is another type of surgical technique providing elbow flexion, with great strength, but very often this muscle innervation (thoracodorsal nerve) is damaged in the brachial plexus injuries

[47]. Preoperative strong latissimus muscle and well passive extension of the elbow are needed for successful unipolar transfer of the latissimus muscle to have good outcome, functional, but also providing good aesthetic outcome [48].

Triceps muscle transfer to biceps muscle is a technique in which the distal part of the triceps tendon is detached, and, then, transferred to the tendon of the biceps. With this transfer, good elbow flexion can be achieved after the process of rehabilitation, where the triceps muscle will learn its new function, but the active extension of the elbow will be lost, making this procedure unwanted for patients who depend on using wheelchair or crutches. Good functional result and solid evaluation from the patients are found in most of the cases, except in cases of inadequate tension at the level of the tendon suture line [49].

3.2.6. Free muscle transfer

Free muscle transfer as a surgical procedure for restoring the function of the upper limb is developed in the last years, together with the development of the microsurgical technique and the consecutive microneural adaptation to the recipient nerve. Tamai et al. [50] in 1970 reported on the first free muscle transfers in dogs that introduce this type of procedure as successful. Free muscle transfer procedure needs to be considered in a patient with brachial plexus injury, with or without preexisting treatment, with no clinical and functional sign of recovery after 9-12 months from the trauma [51, 52]. Accessory nerve, intercostal nerves, fascicle of ulnar nerve or sural nerve are used as a donor motor nerve, providing neurotization to the transferred free muscle in severe trauma of the brachial plexus. Vessels anastomosis and precise adaptation of the nerves are prerequisite for successful free functional muscle transfer. Rectus femoris and gracilis muscle are the ones that are used mostly as a donor muscle [54, 55], followed by latissimus dorsi muscle, greater thoracic and tensor iliotibial band muscle [56].

3.2.7 Bionic reconstruction

In the last few years, bionic reconstruction as a novel treatment approach has been described for treatment of the severe cases with BPI, where there wasn't an improvement in the hand or arm function after the primary and secondary reconstruction procedures. Free muscle or nerve trans-

fer is done first to secure an electromyographic signal sites that will provide control of the bionic hand. The functionless hand is then amputated at the transradial or transhumeral level, depending on the function of the elbow, or even a glenohumeral amputation is performed. It is very important this kind of treatment to be done in carefully selected patients that understood the irreversibility of the treatment options and the need of intense process of rehabilitation and learning [57].

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Резиме**ПОВРЕДИ НА РАМЕНИОТ НЕРВЕН СПЛЕТ –
ПРЕГЛЕД НА АНАТОМИЈА И ОПЦИИ ЗА ТРЕТМАН**

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Повредите на рамениот нервен сплет сè уште се хируршки предизвик за секој хирург што третира пациенти со повреди на БП. Повредите на брахијалниот плексус можат да се поделат на повреди на горното стебло, проширен тип на повреда, повреди на долното стебло и комплетна лезија на сите корени со висечка рака. Разликуваме пет анатомски делови на брахијалниот плексус: корени, стебла, дивизии, снопови и завршни гранки. Завршува со пет терминални гранки одговорни за инервација на горниот екстремитет, мускуло-кожниот нерв, средиштен нерв, пазувен нерв, радијалниот нерв и улнарниот нерв. Во зависност од добиените резултати од предоперативно направените иследување, во комбинација со функционалниот дефицит откриен при клиничкиот преглед, типот на повреда на БП ќе биде установена и ќе се одлучи која е соодветната хируршка процедура за третман на пациентот од повеќето можни процедури (невролиза, нервен трансплантат, невротизација, артроредукција, трансфер на тетиви, слободен мускулен трансфер, бионичка реконструкција), кои се употребуваат при третман на повреди на брахијалниот плексус.

Клучни зборови: ПБП, повреди на брахијален плексус, опции за третман за повреди на брахијалниот плексус, бионичка реконструкција