Original article

Ukr Neurosurg J. 2022;28(4):41-48
doi: 10.25305/unj.265680

Selective surgical reinnervationn of the axillary nerve due to supraclavicular brachial plexus injury: outcomes of 42 consecutive cases, causes of inefficacy

Alexander A. Gatskiy, Ihor B. Tretyak, Vitalii I. Tsymbaliuk, Iaroslav V. Tsymbaliuk, Hao Jiang

Restorative Neurosurgery Department, Romodanov Neurosurgery Institute, Kyiv, Ukraine

Received: 09 October 2022
Accepted: 21 November 2022

Address for correspondence:
Iaroslav V. Tsymbaliuk, Restorative Neurosurgery Department, Romodanov Neurosurgery Institute, 32 Platona Mayborody st., Kyiv, Ukraine, 04050, e-mail: yaroslav.neuro@gmail.com

Objective: retrospective analysis of the outcomes of selective surgical reinnervation (SSR) of the axillary nerve (Ax) in patients with supraclavicular brachial plexus injury (SBPI).

Materials and methods. Forty-two patients (mean age 31.2 years) received 25 SSR with extraplexus donor nerves (e-ND) – 9 cases of subtotal SBPI and 16 cases of complete SBPI. In 17 cases of subtotal SBPI exclusively intraplexus donor nerve (i-ND) were utilized. Twenty-nine (69%) patients received SSR in terms up to 6 months, 13 patients (31%) – in terms more than 6 months. All patients at the time of inclusion were examined neurologically, electophisilogically and in 6, 9, 15 and 17 months. Recovery of the deltoid (D) muscle was assessed on Medical Research Council Scale (MRC Scale) – effective power (Ep). Recovery of effective function (Ef) has been assessed on the basis of flexion angle in glenohumeral joint in sagittal plane.

Results. Ep of D recovered in 12 patients (28%), in terms up to 6 months - in 31%, more than 6 months – in 23%. Ep of D recovered after SSR with i-ND in 9 patients (52%), in terms up to than 6 months - in 60%, more than 6 months – in 43%. Ep of D recovered after SSR with e-ND in 3 patients (12%), in terms up to 6 months- in 16%, no recovery of Ep has been observed in terms more than 6months.

Ef of D recovered in 11 patients (26%), in terms up to 6months - in 31%, more than 6months – in 15%. Ef of D recovered after SSR with i-ND in 8 patients (53%), in terms up to 6 months - in 60%, more than 6 months – in 29%. Ep of D recovered after SSR with e-ND in 3 cases (12%), in terms up to 6months - in 16%, no recovery of Ep has been observed in terms more than 6months. Recovery of Ef of D at subtotal SBPI occurred in 10 cases (38%), regardless of whether i-ND or e-ND have been utilized. SSR with e-ND at subtotal SBPI allowed restoring Ef of D in 2 cases (22%). SSR with i-ND at subtotal SBPI allowed restoring Ef of D in 8 cases (47%). SSR at complete SBPI allowed restoring Ef of D in 1 case (6%).

Conclusions. e-ND can be utilized at complete SBPI in order to provide stability to glenohumeral joint in terms up to 6 months; i-ND should be utilized in all cases of subtotal SBPI in order to provide Ef to D in terms up to 6 months.

Key words: *injury; brachial plexus; selective surgical reinnervation; nerve transfer; axillary nerve*

Introduction

Supraclavicular brachial plexus injuries (SBPI) result in long-term and sustained global or segmental dysfunction of the upper extremity [1]. Even with modern electrophysiological [2–4] and radiological [5–8] examination methods, evaluating the possibility of spontaneous recovery is an extremely difficult task with no guarantee of success [1]. The expectation of probable spontaneous recovery (SR) is clearly time-bound [1, 9], in other words, the terms are determined [1, 9] beyond which one should not hope for the restoration of the lost function [1, 9]. Waiting for recovery is by no means a passive process. During a certain [9] period of time allocated to SR, an active multimodal impact on the recovery process using protocol [10] conservative treatment methods is carried out.

As the critical deadline set for SR approaches, and in the absence of objective, primarily clinical [9], data on the restoration of lost function, the need for surgical reconstructive techniques becomes paramount [9]. The fundamental difference between conventional surgical methods of influencing the regenerative process is their aggressiveness and selectivity [1, 11–13]. Accordingly, they can be arranged in the following order according to the degree of aggressiveness/selectivity: neurolysis, autologous plasty, and reinnervation. Each of them has certain advantages and disadvantages, limitations in use, etc. [1, 11–14].

During the last decade, the increased use of a more aggressive and selective surgical technique for the regenerative process - selective surgical reinnervation (SSR) has led to a dramatic change in the approach to the treatment of not only traumatic brachial plexus injuries, but also injuries to the structures of the peripheral nervous system (PNS) in general [11, 12]. Numerous SSR techniques developed and put into practice make it possible to achieve the predictable functional result within a prognostic period [9, 11, 12]. The priority of segmental functions restoration in case of the upper limb PNS structures damage at any level has been determined [1], reliable potential donor nerves (ND) and acceptor nerves (NA) have been identified accordingly.

The only objective limitation of the possibility of using the SSR method, apart from the time factor [9], is the specific anatomy of damage to PNS structures, in particular supraclavicular brachial plexus injury (SBPI). This limitation is caused by a decrease in the number and, consequently, the availability of potential intraplexus ipsilateral ND (i-ND) as the number of C5-D1 (sometimes – C4-D2) anterior spinal nerves branches involved in the pathological traumatic process increases [9, 12, 15]. In this context, total SBPI has the greatest limitations: only extraplexus ipsilateral ND (e-ND) or contralateral ND are available.

The priority of muscles and their groups renewal in case of damage to the BP structures is of crucial importance for global upper limb function [1]. The highest priority for the overall upper limb functional capacity is the flexion of elbow joint (1st order of priority) [1]. Involvement of all possible e-ND and i-ND when performing the SSR is aimed at restoring exactly the 1st order priority function. The next priority function (2nd order of priority) is stability and multiaxial movements in the glenohumeral joint. The stability of the shoulder girdle, to a certain extent, can be provided by the preserved function of only the axioscapular group of muscles (trapezius, major and minor rhomboid muscles, levator scapula muscle [16]), the innervation of which is provided by nerve structures outside the BP. On the other hand, active multiaxial movements in the shoulder joint are provided by muscles from the innervation pool of the BP - the innervation pool of the axillary (Ax) and suprascapular (SS) nerves, respectively, the probability of their recovery with the help of SSR is even more dependent on both the order of recovery (2nd order) in a certain order of priority, and the anatomy of the SBPI.

Traditionally, the effectiveness of motor function restoration by any conservative or surgical method is determined by assessing the effective power of a muscle (or groups of muscles that provide multiaxial movements in a particular joint, often from different innervation pools) using the Medical Research Council Scale (MRC Scale) [17]. However, the effective power of a muscle or groups of muscles in normal and pathological conditions do not imply the ability of these muscles to perform a function effectively [18]. The effiectve function of a muscle or group of muscles of any segment of the upper limb, the maximum effective range of motion (eROM) in a joint of the segmental apparatus, which they provide, differs significantly from the maximum possible range of motion (mROM).

The key muscle [16] from the Ax innervation pool – the deltoid muscle (D) ensures the implementation of its main function - mainly flexion in the shoulder joint (sagittal plane) [16], as well as the shoulder abduction [16] (frontal plane), mROM in the shoulder joint in the sagittal plane, which is provided by D, is equal to 180° [18]. Dynamic analysis of the activities of daily (ADL) monomanual and bimanual living suggests that the eROM in the shoulder joint in the sagittal plane is equal to 108° [18], respectively, the effective restoration of the effective power (Ep) of D and its effective function (Ef) is the main task of the SSR.

Purpose: to retrospectively analyse the results of selective surgical reinnervation of the axillary nerve in patients with supraclavicular brachial plexus injuries.

Study objectives:

1) to evaluate the results of restoration of effective power and effective function of D after performing SSR Ax;

2) to determine the main factors affecting the effectiveness/ineffectiveness of SSR Ax in patients with SBPI.

Materials and methods

Study participants

Sixty-eight patients (57 males and 11 females) with SBPI (level 1-3 according to D.C. Chuang classification [13]) were enrolled in the study. Informed and voluntary written consent to participate in the study was obtained from all patients. The study was approved by the Committee on Ethics of the Institute of Neurosurgery named after Acad. A. P. Romodanov, Ukraine (Minutes №3 dated November 22, 2021).

Inclusion criteria:

Patients without age restrictions; presence of clinically verified SBPI (including gunshot character); postoperative follow-up period of at least 15 months; patients who underwent surgical intervention using methods of neurolysis, autologous plasty and SSR.

Characteristics of the patient cohort

A simplified approach was used to form the cohort of patients according to D.C. Chuang classification. Thus, all injuries according to the closed type (without damage to the soft tissue surface and deep structures of the lateral triangle of the neck) of the SBPI corresponded to level 1-2 according to D.C. Chuang classification, while injuries according to the open type corresponded to level 3. The simplified approach is due to the inability to perform visualization structures of the BP/cervical spine in the pre-surgical period using computer and magnetic resonance imaging during 2013-2014, to accurately identify cases with preganglionic and postganglionic tears or a mixed nature of injury [13].

In 63 (92%) patients SBPI was due to a high-energy closed traction injury without disrution of the integrity of the superficial and deep soft tissue structures of the lateral neck triangle without/with fracture/

This article contains some figures that are displayed in color online but in black and white in the print edition osteosynthesis of the clavicle (level 1-2 according to D.C Chuang classification), in 5 (8%) individuals with open injury to BP structures in the lateral triangle of the neck (level 3).

The mean age of the patients was 28.4 years (from 0.5 to 72 years). The average time from the moment of injury to the time of SSR was 7.4 months (from 2 weeks to 6 years). Forty-six (68%) patients underwent SSR (selective surgical reinnervation) within 6 months, 22 (32%) after 6 months. In the cohort of 68 patients involved in the study, the anatomical characteristics of SBPI were as follows: damage to the anterior branches of the spinal nerves (hereinafter only the number of the spinal nerve is indicated) C5 – 1 (1.5%) case, C5-C6 – 18 (27%), C5-C6-C7 – 22 (32%), C5-C6-C7-C8 – 1 (1.5%), C5-C6-C7-C8-D1 (total version of SBPI) – 26 (38%).

The formation of patients cohort was based on the confirmed fact of selective reinnervation (SSR), aimed at restoring the priority function of the 1st and 2nd orders in one patient (or the priority function of any one order, or their combination), as well as the combination of orders and suborders (innervation pools for the priority function of the 2nd order - Ax/SS), respectively, the number of patients in the study corresponds to the absolute number of cases of SSR in the study (68 patients underwent 68 SSR): 55 SSR aimed at restoring the 1st order priority function, 42 SSR aimed at restoring the 2nd order priority function (suborder 2, innervation pool Ax) and 29 SSR aimed at restoring the 2nd order priority function (suborder 2, innervation pool SS) ***(Table 1)***.

The study group was formed on the basis only on the confirmed fact of performing SSR aimed at restoring the 2nd order priority function - Ax surgical reinnervation (suborder 2), regardless of the existing cases of combining SSR aimed at restoring other functions in the order or suborder of their priority, respectively, the group consisted of 42 patients. The average age of the patients was 31.2 years. Twenty-nine (69%) patients underwent SSR Ax within 6 months, 13 (31%) - after 6 months. In this group, the anatomical characteristics of SBPI were as follows: C5-C6 in 14 cases (33% in the study group and 21% in the cohort of patients in the study), C5-C6-C7 in 12 (respectively 29 and 18%), C5-C6-C7-C8-D1 (total version of SBPI, hereinafter - total) in 16 (38 and 24%).

Study design

Analytical controlled retrospective cohort single-center study conducted during 2013–2019.

Characteristics of surgical interventions

Selective surgical reinnervation of Ax in the study group of patients was performed using standard techniques described in numerous literature sources over the past 20 years [11,12]. Donor nerves used in SSR can be divided into two main subgroups - i-ND and e-ND. The main i-ND (17 cases of use, 41%) were the radial nerve branches to the caput mediale of the triceps brachii muscle (RN (CMTB)) in 14 (33%) cases and common trunk of the thoracodorsal nerve (ThorDors) in 1 (2%). In two cases, the anterior branch of the anterior spinal nerve C5 was used as i-ND in the absence of other ipsilateral i-ND and e-ND and the macroscopic integrity of the latter was preserved (the viability of the proximal C5 stump was not determined using standard morphological methods [19] during surgery) - "donor of despair". Various branches of the accessory nerve (Acc) were used as the main source of e-ND (25 cases of use, 41%).

In the majority of cases, the choice in favor of i-ND or e-ND was due to the anatomy of the SBPI (total lesion variants): there was no alternative to e-ND in 16 (38%) cases. In the case of subtotal SBPI variants, preference was given to the use of i-ND over e-ND (15 and 9 excluding "donors of despair").

The main fundamental technical difference between the use of e-ND and i-ND was the need to perform the interposition of an autologous nerve graft (the size of which significantly exceeded the critical dimensions of the peripheral nerve defect [14]) between the e-ND and the recipient nerve (NR) and direct anastomosis of the i-ND -NR, respectively. In all cases of using both e-ND and i-ND, total (complete or non-selective with respect to Ax branches) reinnervation of Ax was performed.

Evaluation of results

All patients included in the study were instructed to restore lost function and follow standardized rehabilitation programs 3 months after SSR. All patients

Table 1. Number of cases of selective surgical reinnervation aimed at restoring the 1st and 2nd orders priority function in one patient, or any one order or their combination, as well as the combination of orders and suborders (innervation pools for 2nd order priority function– Ax/SS) in the patient cohort

<table>
<tr><th>Priority order</th><th>PF of the 2nd order</th><th rowspan="2">PF of the 1st order</th><th>PF of the 2nd order</th></tr>
<tr><td>Suborder</td><td>Ax pool</td><td>SS pool</td></tr>
<tr><td>Only one PF (sum of facts of SSR performance for one PF only)</td><td>42</td><td>55</td><td>29</td></tr>
<tr><td>PF1+PF2 (Ax+SS)</td><td colspan="3">12</td></tr>
<tr><td>PF1+PF2 (Ax)</td><td colspan="2">35</td><td></td></tr>
<tr><td>PF1+PF2 (SS)</td><td></td><td colspan="2">8</td></tr>
<tr><td>PF2 (Ax+SS)</td><td>20</td><td></td><td>20</td></tr>
</table>

Note: PF - function priority (according to M.G. Siqueira et al. [1]); Ax – axillary nerve; SS – suprascapular nerve.

underwent a neurological examination after SSR, supplemented with an electrophysiological examination (electroneuromyography) according to the standard method after 6, 9, 15 and 17 months. Rehabilitation programs after SSR were formed according to the specific functions initially provided by the ND used during surgery: patients were instructed on the need to perform specific motor exercises both under the supervision of a rehabilitation physician and independently at home.

The primary aim of the neurological examination was to evaluate the effective power of D recovery according to the MRC Scale [17]: recovery of function to the M4-5 level was considered to be an effective recovery of effective power (Ep). The functional efficiency of the effective power of D was evaluated by measuring the flexion angle in the glenohumeral joint in sagittal plane. Effective function (Ef) was considered effective if D restored to M4-5 was able to provide flexion in the glenohumeral joint ≥108° (eROM). The requirement for flexion in the glenohumeral joint in the sagittal plane is based on the peak values of angular activity D when performing most activities of daily living (ADL) [18].

Needle and surface electroneuromyography were mainly used in the early (after 9 and 12 months) and late (after 15 and 17 months) periods after SSR to confirm ineffective reinnervation or lack of activity in D, making it possible to recommend orthopedic corrective interventions (transposition of tendon-muscle complex/complexes) to restore flexion in the glenohumeral joint in those cases where it was possible.

Statistical analysis

There were limitations of the study when conducting statistical data processing. Thus, significant heterogeneity of characteristics (age, gender, terms of injury, etc.) did not allow groups based on similar characteristics to be formed for statistical analysis.

Results and their discussion

Among 42 patients from the study group, clinical signs (from M2 to M5) of D reinnervation were achieved in 25 (59%) cases ***(Fig. 1)***. In 17 (41%) cases, D reinnervation did not occur after performing SSR. Within 6 months, D reinnervation was achieved in 16 (55%) patients, after 6 months - in 13 (69%). Restoration of effective power (Ep) D was achieved in 12 (28%) patients (before 6 months - in 9 (31%), later than 6 months - in 3 (23%)). The ratio of cases of effective (M4-5), ineffective (M2-3) and absence of reinnervation D according to the research results was 12:13:17.

The use of i-ND made it possible to achieve clinical signs of D reinnervation in 12 patients (71% of cases using all i-ND and 80% excluding "donors of despair"), within 6 months - in 8 patients (80% of all cases using i-ND in this period and in 100% of cases excluding "donors of despair"), 6 months later - in 4 patients (57%). Recovery of Ep D when using i-ND was achieved in 9 (52%) patients (up to 6 months - in 6 (60%), after 6 months - in 3 (43%)). The ratio of cases of effective (M4-5), ineffective (M2-3) and absence of D reinnervation when using i-ND was 9:3:5.

The use of e-ND resulted in clinical evidence of D reinnervation in 13 (42%) patients (up to 6 months - in 8 patients (42% of all cases using e-ND at this time), after 6 months - in 5 (83%)). Recovery of EP D when using e-ND was achieved in 3 (12%) patients (up to 6 months - in 3 (16%), later than 6 months - in none). The ratio of cases of effective (M4-5), ineffective (M2-3) and absence of D reinnervation when using e-ND was 3:10:12.

Clinical signs of restoration of effective function (Ef) D (under conditions of restoration of Ep) were achieved in 11 (26%) cases, regardless of the timing of SSR ***(Fig. 1)*** (up to 6 months - in 9 (31%), after 6 months – in 2 (15%)).

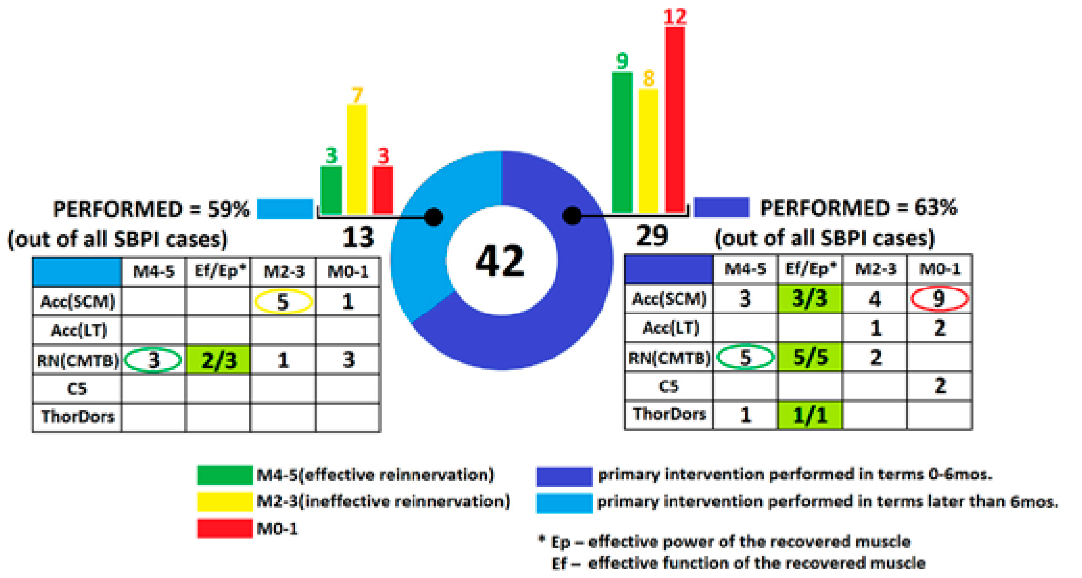
The use of i-ND made it possible to achieve restoration of Ef D in 8 (53%) cases (before 6 months - in 6 (60%), after 6 months - in 3 (29%)). The ratio of cases of recovery of Ef in the case of recovery of effective Ep D when using i-ND was 8:9.

The use of e-ND made it possible to achieve recovery of Ef D in 3 (12%) cases (up to 6 months - in 3 (16%), later than 6 months - in none). The ratio of cases of recovery of Ef in the case of recovery of effective Ep D when using i-ND was 3:3.

Recovery of Ef D in subtotal variants of SBPI was achieved in 10 cases when using both i-ND and e-ND (38% efficacy). The use of e-ND in subtotal variants of SBPI resulted in Ef D recovery in 2 cases (22% efficacy), the use of i-ND in 8 (47% efficacy). Recovery of Ef D with total variants of SBPI was achieved in 1 case (6% efficacy).

The main goal of surgical reinnervation of muscular structures is to restore their effective function. The processes accompanying both spontaneous and surgically induced recovery are subject to well-known physiological mechanisms of recovery of PNS structures [20]. The main factors influencing the efficiency of motor function recovery are the distance from the site of damage to the PNS structure to the effector muscle and the integral time indicator, i.e. the sum of the time from the moment of damage and the predicted time of muscle reinnervation [9, 20].

Surgically induced selective reinnervation (SSR) is able to modify the influence of the above-mentioned factors, by modifying the "distance" factor and, consequently, the "time factor" component (predicted period of muscle reinnervation). In other words, the recruitment of nerves that can potentially become donors of motor fibers (which also have certain requirements [20, 21]) should take place in close proximity to a muscle or a group of muscles from the same innervation pool. Adherence to this principle allows the negative impact of the "distance" factor and the component of the "time" factor to be reduced to a certain extent. This statement is reflected in the basic principles of effective use of the SSP technique [9, 14, 20]. The effectiveness of the SSR technique depends on another factor that cannot be modified under any circumstances, the factor of "anatomical characteristics" of damage to PNS structures. In the context of using the SSR technique, the derivative of this factor – the subfactor of "accessibility/availability" of motor fiber ND – is of the greatest importance. It is well known that the most severe injuries of PNS structures are supraclavicular and subclavicular injuries of the BP, respectively, the anatomical characteristics of the damage of the BP to a greater extent affect the accessibility/availability of ND in close proximity to the muscle whose function needs to be restored. Since the source of such ND is



	M4-5	Ef/Ep*	M2-3	M0-1
Acc(SCM)			5	1
Acc(LT)				
RN(CMTB)	3	2/3	1	3
C5				
ThorDors				

	M4-5	Ef/Ep*	M2-3	M0-1
Acc(SCM)	3	3/3	4	9
Acc(LT)			1	2
RN(CMTB)	5	5/5	2	
C5				2
ThorDors	1	1/1		

Fig. 1. Effectiveness of restoring the effective power of the deltoid muscle as a result of reinnervation with the involvement of donor nerves of extraplexus and intraplexus origin up to 6 months and after 6 months after supraclavicular brachial plexus injuries: *Acc(SCM) - pars sternocleidomastoideus nervi accessorii; Acc (LT) – pars trapezoideus (to pars ascendens of trapezius muscle) nervi accessorii; RN(CMTB) - motor branches n. radialis (from 1-3 pcs.) to caput mediale m. triceps brachii; C5 – the stump of the anterior branch of the C5 spinal nerve; ThorDors – common trunk of the thoracodorsal nerve; RI - reconstructive intervention*

mostly the damaged BP itself (i-ND), the "anatomical characteristics" factor of the injury can minimize the advantages of the SSR technique (decrease the number of accessible/available i-ND), forcing the use of e-ND.

The correlation between the use of ND on the anatomy of the SBPI in this study is presented in ***Table 2.***

It is noteworthy that only e-ND was used in the study group when performing SSR in all total SBPI variants, whereas the SSR in subtotal variants of SBPI was performed with the involvement of i-ND in 17 cases and e-ND in 9 (36% of all cases using e-ND).

Since e-NDs are located at a considerable distance from the muscle to be restored, the factor of "anatomical characteristics" of the injury directly affects the factor of "distance" and indirectly - the component of the factor of "time". The resulting influence of the mentioned factors leads to ineffective reinnervation or no recovery of muscle function at all. This factor influence is confirmed by the low rate of effective Ep and Ef D recovery after the SSR involving e-ND both in subtotal (22% of cases for Ep and Ef from those performed) and in total (6% of cases for Ep and Ef from those performed) variants of SBPI ***(Fig. 2)***.

The use of different branches of the accessory nerve (Acc) at a considerable distance from the Ax (10–18 cm) significantly increased the influence of the "distance" factor and the "time" factor component. Conversely, the presence of available i-ND in the close vicinity of Ax with subtotal SBPI largely neutralized the influence of the "distance" factor and the "time" factor component. This is confirmed by the high rate of recovery of Ep and Ef D after SSR involving i-ND with subtotal SBPI: 60% of those carried out without taking into account the use of "donors of despair" - for Ep and 53% - for Ef ***(Fig. 2)***.

Elimination of another component of the "time" factor (modulation (reduction) of the time from the moment of injury to the SSR performance involving i-ND at up to 6 months) increased the frequency of recovery of Ep and Ef D to 75% (without taking into account the effectiveness of using "donors of despair") .

Beyond the purely "mechanistic" analysis of the results of using SSR, aimed at restoring the priority function of the 2nd order (suborder 2, innervation pool Ax, D), by identifying the connections between the reasons of effectiveness/ ineffectiveness of SSR and factors (as well as their components) of time and distance, an equally important factor is the "philosophical" component - the "readiness" of the profile specialist to use more aggressive surgical methods of selective reinnervation. Thus, during 2013-2019 and as positive results of SSR were obtained in general, an absolute "readiness" of profile specialists to use more aggressive surgical approaches (SSR) was formed in order of priority when restoring the upper limb functions. After receiving numerous negative results when using "traditional" methods (techniques) of SSR using e-ND (Acc) regardless of the anatomical characteristics of the injury (with total and subtotal variants of SBPI characterized by the presence of available i-ND) and impact analysis component factors of time and distance (during the 2013–2015 study), there was a need for intensive use of "new" (which had not been used at all or by a particular specialist) methods (techniques) of SSR involving new NDs. In the study group, during 2013–2019, 3 "new" techniques of SSR D - SSR Ax were introduced (its portions - superselectivity) involving as i-ND the radial nerve branch to the caput mediale of the triceps brachii muscle (RN(CMTB)), common trunk

Table 2. Dependence of the origin of the donor nerves used in the study on the anatomical characteristics of supraclavicular brachial plexus injuries

Anatomy of SBPI	Number of cases	Origin of ipsilateral ND			
		e-ND		i-ND	
		Utilized	Total	Utilized	Total
Subtotal variants 26 (C5-C6 and C5-C6-C7)	26	9	25	17	17
Total variant	16	16	25	0	17

Note: ND – nerve donor; e-ND – extraplexus nerve donors; i-ND – intraplexus nerve donors.

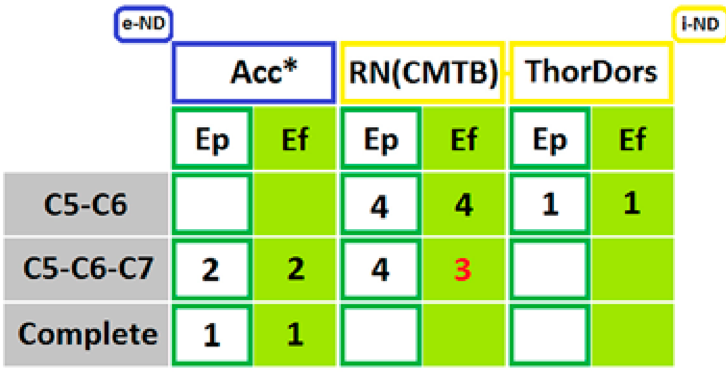


Fig. 2. Dependence of restoration of effective power and effective deltoid muscle function after selective surgical reinnervation of the axillary nerve when using donor nerves of extraplexus and intraplexus origin on the anatomical characteristics of supraclavicular brachial plexus injuries: *e-ND - extraplexus donor nerves; i-ND - intraplexus donor nerves; Acc – nervus accessorius; RN(CMTB) - motor branches n. radialis (from 1-3 pcs.) to caput mediale m. triceps brachii; ThorDors – common trunk of thoracodorsal nerve; Total – total variant of SBPI; * – generalized for all possible SSR techniques involving only Acc (any branches from any approach)*

or portion of the thoracodorsal nerve (ThorDors) and as e-ND - branches of the accessory nerve to pars ascendens of trapezius muscle (Acc(LT)). The expansion of the ND spectrum, which is directly related to the change in the philosophy of using selective reinnervation techniques, is shown in ***Fig. 3***. The use of e-ND did not allow leveling the "time" factor component (time given for recovery) and aggravated the problem of the "distance" factor (the distance from the ND to the nerve-acceptor – muscle-effector) both in total and subtotal variants of SBPI: the overall effectiveness of "traditional" methods allowed to restore Ep D in total only in 12% of cases used ***(Fig. 3)***. Active introduction of "new techniques" of the SSR made it possible to level the "time" factor component (time allocated for recovery) to a certain extent and to completely solve the problem of the "distance" factor in subtotal variants of the SBPI: the overall effectiveness of the "new" techniques made it possible to restore Ep D in total in 53% of cases of use ***(Fig. 3)***.

Consequently, consideration of the influence of many factors (time, distance, anatomical characteristics of the injury) is the key to effective individualized and systemic use of the SSR technique in case of damage to any PNS structures of any limb at any level.

Conclusions

1. The use of extraplexus donor nerves (branches of the nervus accessorius) for reinnervation of the axillary nerve is ineffective in the context of providing the restoration of effective power and function of the deltoid muscle in supraclavicular brachial plexus injuries (achieved in only 12% of patients).
2. The use of extraplexus donor nerves (branches of the nervus accessorius) may be justified to ensure stability of the glenohumeral joint (restoration of the deltoid muscle to M2-3) (achieved in 40% of patients).
3. The use of intraplexus donor nerves is effective in the context of providing the restoration of effective

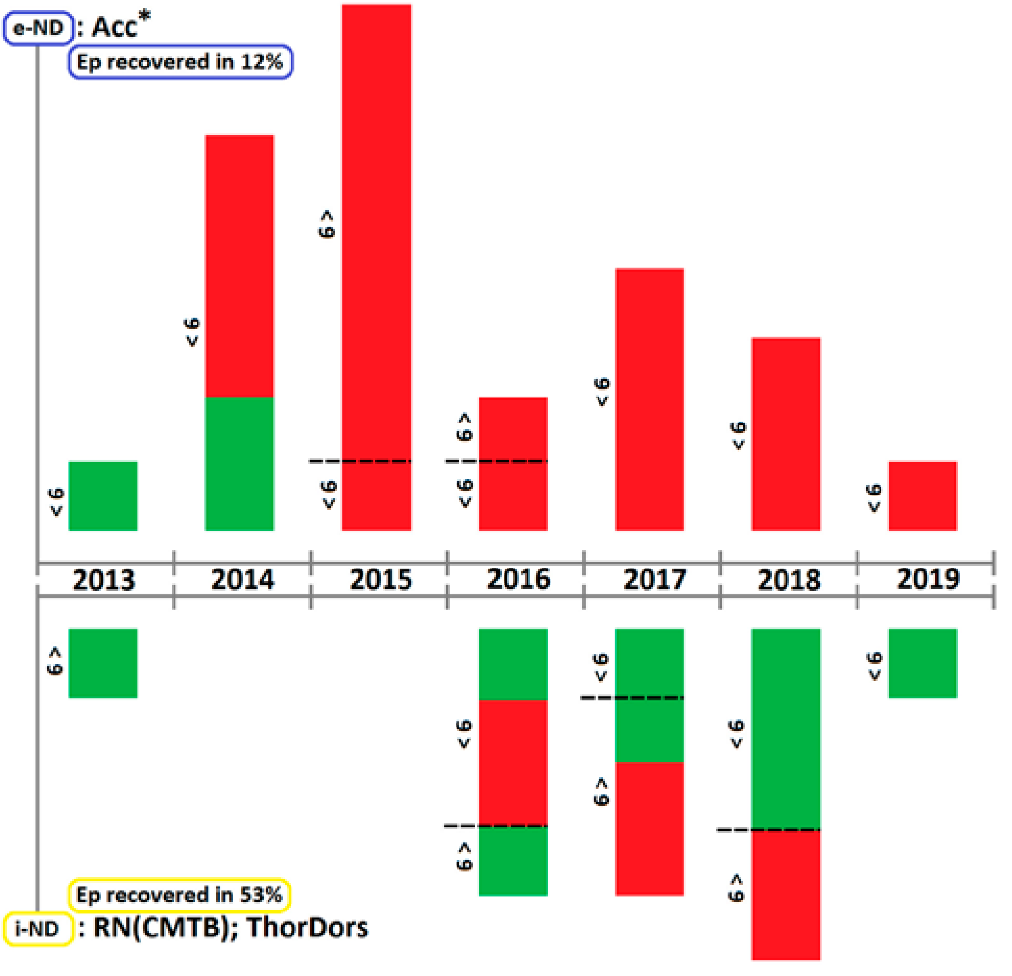


Fig. 3. Dynamics of using "traditional" and "new" methods (techniques) of selective surgical reinnervation of the axillary nerve involving donor nerves of extraplexus and intraplexus origin during 2013-2019: *e-ND - extraplexus donor nerves; i-ND - intraplexus donor nerves; Acc – nervus accessorius; RN(CMTB) - motor branches n. radialis (from 1–3 pcs.) to caput mediale m. triceps brachii; ThorDors – common trunk of thoracodorsal nerve; >6 – performance of SSR later than 6 months after injury; <6 – performance of SSR within 6 months after injury; Ep - effective power of the muscle (M4-5 according to the MRC Scale); green color – effective restoration of power of the deltoid muscle; red color – ineffective restoration of power of the deltoid muscle (M1-3 according to the MRC Scale); * – generalized for all possible SSR techniques involving only Acc (any branches at any approach)*

power and effective function of the deltoid muscle in subtotal supraclavicular brachial plexus injuries (achieved in 53% of patients).

4. Extraplexus donor nerves (branches of the nervus accessorius) should not be used for axillary nerve reinnervation in patients with subtotal variants of supraclavicular brachial plexus injuries.

5. Extraplexus donor nerves (branches of the nervus accessorius) should be used for axillary nerve reinnervation in patients with total variants of supraclavicular brachial plexus injuries.

6. Modulation (reduction) of the time from the moment of injury to selective reinnervation of the axillary nerve is mandatory when performing selective reinnervation using both extraplexus and intraplexus donor nerves in appropriate variants of supraclavicular brachial plexus injuries.

7. The period of 6 months from the moment of injury to selective reinnervation by any technique should be considered critical for achieving restoration of effective power and effective function of the deltoid muscle in subtotal supraclavicular brachial plexus injuries (achieved in 75% of patients).

8. Performing selective reinnervation using both extraplexus and intraplexus donor nerves in appropriate variants of supraclavicular brachial plexus injuries later than 6 months after injury allows restoration of glenohumeral joint stability (achieved in 46% of patients).

Information disclosure

Conflict of interest

The authors declare no conflict of interest.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent

Informed and voluntary written consent to participate in the study was obtained from all patients.

Funding

The study was not sponsored.

References

1. Siqueira MG, Martins RS. Surgical treatment of adult traumatic brachial plexus injuries: an overview. Arq Neuropsiquiatr. 2011 Jun;69(3):528-35. doi: 10.1590/s0004-282x2011000400023
2. Warren J, Gutmann L, Figueroa AF Jr, Bloor BM. Electromyographic changes of brachial plexus root avulsions. J Neurosurg. 1969 Aug;31(2):137-40. doi: 10.3171/jns.1969.31.2.0137
3. Landi A, Copeland SA, Parry CB, Jones SJ. The role of somatosensory evoked potentials and nerve conduction studies in the surgical management of brachial plexus injuries. J Bone Joint Surg Br. 1980 Nov;62-B(4):492-6. doi: 10.1302/0301-620X.62B4.7430231
4. Kline DG, Happel LT. Penfield Lecture. A quarter century's experience with intraoperative nerve action potential recording. Can J Neurol Sci. 1993 Feb;20(1):3-10. doi: 10.1017/s0317167100047338
5. Carvalho GA, Nikkhah G, Matthies C, Penkert G, Samii M. Diagnosis of root avulsions in traumatic brachial plexus injuries: value of computerized tomography myelography and magnetic resonance imaging. J Neurosurg. 1997 Jan;86(1):69-76. doi: 10.3171/jns.1997.86.1.0069
6. Walker AT, Chaloupka JC, de Lotbiniere AC, Wolfe SW, Goldman R, Kier EL. Detection of nerve rootlet avulsion on CT myelography in patients with birth palsy and brachial plexus injury after trauma. AJR Am J Roentgenol. 1996 Nov;167(5):1283-7. doi: 10.2214/ajr.167.5.8911196
7. Nakamura T, Yabe Y, Horiuchi Y, Takayama S. Magnetic resonance myelography in brachial plexus injury. J Bone Joint Surg Br. 1997 Sep;79(5):764-9. doi: 10.1302/0301-620x.79b5.7679
8. Doi K, Otsuka K, Okamoto Y, Fujii H, Hattori Y, Baliarsing AS. Cervical nerve root avulsion in brachial plexus injuries: magnetic resonance imaging classification and comparison with myelography and computerized tomography myelography. J Neurosurg. 2002 Apr;96(3 Suppl):277-84. doi: 10.3171/spi.2002.96.3.0277
9. Martin E, Senders JT, DiRisio AC, Smith TR, Broekman MLD. Timing of surgery in traumatic brachial plexus injury: a systematic review. J Neurosurg. 2018 May 1:1-13. doi: 10.3171/2018.1.JNS172068
10. Standardization in neurosurgery. Part 2. Neuro-oncology. Kyiv: Romodanov Neurosurgery Institute, 2020. 144 p.
11. Moore AM. Nerve Transfers to Restore upper Extremity Function: A Paradigm Shift. Front Neurol. 2014 Mar 31;5:40. doi: 10.3389/fneur.2014.00040
12. Hems T. Nerve transfers for traumatic brachial plexus injury: advantages and problems. J Hand Microsurg. 2011 Jun;3(1):6-10. doi: 10.1007/s12593-011-0031-1
13. Chuang DC. Brachial plexus reconstruction based on the new definition of level of injury. Injury. 2008 Sep;39 Suppl 3:S23-9. doi: 10.1016/j.injury.2008.05.012
14. Socolovsky M, Di Masi G, Battaglia D. Use of long autologous nerve grafts in brachial plexus reconstruction: factors that affect the outcome. Acta Neurochir (Wien). 2011 Nov;153(11):2231-40. doi: 10.1007/s00701-011-1131-1
15. Sakellariou VI, Badilas NK, Stavropoulos NA, Mazis G, Kotoulas HK, Kyriakopoulos S, Tagkalegkas I, Sofianos IP. Treatment options for brachial plexus injuries. ISRN Orthop. 2014 Apr 14;2014:314137. doi: 10.1155/2014/314137
16. Oatis CA. Kinesiology : the Mechanics and Pathomechanics of Human Movement. Third edition. Wolters Kluwer; 2017.
17. Matthews WB. Aids to the examination of the peripheral nervous system. J Neurol Sci. 1977;33(1-2):299.
18. Gates DH, Walters LS, Cowley J, Wilken JM, Resnik L. Range of Motion Requirements for Upper-Limb Activities of Daily Living. Am J Occup Ther. 2016 Jan-Feb;70(1):7001350010p1-7001350010p10. doi: 10.5014/ajot.2016.015487
19. Meyer R, Claussen GC, Oh SJ. Modified trichrome staining technique of the nerve to determine proximal nerve viability. Microsurgery. 1995;16(3):129-32. doi: 10.1002/micr.1920160302
20. Mackinnon SE. Nerve Surgery. New York: Thieme; 2015.
21. Zhang D, Varadharajan V, Bhardwaj P, Venkatramani H, Sabapathy SR. Considerations in the Selection of Donor Nerves for Nerve Transfer for Reanimation of Elbow and Shoulder in Traumatic Brachial Plexus Injuries. J Hand Surg Asian Pac Vol. 2022 Feb;27(1):10-21. doi: 10.1142/S242483552230002X