Original article

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Changing the concept of surgical treatment of the brachial plexus traumatic injuries

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Objective: the objective of this study was to retrospectively analyze the change in the surgical strategy (SS) of brachial plexus injuries (BPI), the outcomes of different SS and the factors that influenced the establishing process of a new SS in a single surgical centre in Kyiv, Ukraine.

Materials and Methods. 148 patients (mean age 29.5) received 76 neurolysis (N), 14 grafting (G) and 58 nerve transfer (NT) surgeries after a mean 7.4 months following BPI. 29 patients received NT of n. phrenicus, 7 –ulnar nerve fascicles, 9 – lateral pectoral nerve, 7 – medial pectoral nerve to musculocutaneous nerve aimed to restore active elbow flexion. Six other patients received NT of ipsilateral extraplexal motor nerves. The follow-up period included neurological examination (MRC Scale), electromyographic examination and angular deviation in the elbow joint during recovered active elbow flexion. 148 patients were retrospectively divided into two groups A (102 patients, received surgeries from surgical team #1) and B (46 patients, received surgeries from surgical team #2). The SS used in each group and its change with time was analyzed during the 6-year span.

Results. 41 patients (70.7%) showed recovery of effective power (Ep) (M4-5) of biceps brachii muscle (BB) after NT. 14 patients (18.4%) showed recovery of Ep of BB after N. 4 patients (28.6%) showed recovery of Ep of BB after G. Overall Group A patients received 55 NT, Group B – 3 NT. The number of NT among Group A patients increased in 2013-2019 from 31% to 100% with overall efficacy of NT increased from 50% to 83%.

Conclusions. SS of BPI changed only for Group A patients – N was completely replaced by NT in 2019. For Group B patients N remained SS of choice. The establishing of new SS was influenced by four factors (time, anatomy of injury, donor nerves, radiological findings). The factors being processed, allowed us to define optimal time, effective donors and non-reliability of radiology at BPI. We state that it is only matter of own experience, based on the thorough analysis of the technique, that brings positive outcomes after new SS has been adopted.

Key words: *brachial plexus; trauma; surgical treatment; nerve transfer; nerve grafting*

Introduction

The main goal of treating damage to the structures of peripheral nervous system (PNS) is to restore the lost function, which is achieved using different surgical methods (with a certain system of principles for each of them), remains unchanged for a long time, while the methodology of surgical techniques, one of the tasks of which is determining the effectiveness and limits of productive use of each of them has undergone significant changes over the past decades [1,2].

It is well known that the experimental and notably clinical use of any of the surgical methods was preceded by an assumptions about their potential to best meet the main goal. Each of the hypotheses underwent stages of formulation, substantiation, accumulation of data and verification of outcomes in practice in the experiment and clinic. The ability to predictably achieve the main goal with the certain efficiency made it possible to use each of the surgical methods within understanding the concept of phenomena and processes. Each of the dominant (preferred among others) concepts in a certain period of time corresponds to the use of a defined and dominant (preferred) surgical method.

Historical reviews of literature sources [1,2] show the emergence and authenticity of two hypotheses, two global changes in dominant concepts and, accordingly, two methods of surgical treatment of damage to PNS structures, accompanied by the preservation of hereditary links between hypotheses, concepts and methods within the limits of prior knowledge.

During the 1960s and at the end of the first decade of the XXI century, the use of grafting and nerve transfer (NT) as the dominant surgical methods contributed to the confirmation of hypotheses which were the basis for the emergence of new concepts proven by clinical results, consistent with the main goal in surgical treatment of damage to PNS structures [1,2]. In addition to the ability to ensure the achievement of the main goal, each of the concepts that dominated in a certain period of time had a common feature - universalism, which consisted in the ability to ensure the recovery of any function in case of damage to any nerve of any segment of any limb. The obtained clinical and experimental results in the field of PNS surgery over the past two decades indicate the approval of selective reinnervation (nerve transfer) as the dominant concept and, accordingly, the dominant method - [1,2]. Due to the emergence of a large number of new surgical techniques of selective reinnervation using a variety of donor nerves [3], the method of nerve transfer corresponded to the main goal and became a universal method [1,2].

The popularization of the new concept with the help of the "digital universe" made it possible to reproduce the proposed surgical techniques in any part of the world [4].

However, the adoption of a new concept and the introduction of new surgical techniques (within this concept) into daily clinical practice does not occur immediately and simultaneously around the world. More often, the process of adopting a new concept is long, even for specialists of one surgical center - from providing insight into basic postulates, limited use of selective techniques to the full adoption and implementation of all existing techniques with proven effectiveness in routine surgical practice. The full viability of a new concept can only be proven by clinical results.

Objective: the objective of this study was to retrospectively analyze the change in the surgical strategy (SS) of brachial plexus injuries (BPI), the outcomes of different SS and the factors that influenced the establishing process of a new SS in a single surgical centre in Kyiv, Ukraine.

Materials and Methods

Study particiants

The study involved 149 patients (127 males and 22 females) with supraclavicular traumatic injuries (STI) of the brachial plexus (BP) - level 1-3 according to the classification of D.C. Chuang [5], who underwent surgical treatment in 2013–2019. Informed and voluntary written consent to participate in the study was obtained from all patients..

The study was approved by the Committee on Ethics and Bioethics of the Institute of Neurosurgery named after acad. A. P. Romodanov, Ukraine (Minutes №3 dated November 22, 2021).

Inclusion criteria:

Patients without age restrictions; the presence of verified damage to BP (STI); postoperative follow-up period – is at least 15 months; patients who have been treated with neurolysis, nerve transfer, or grafing of BP.

Characteristics of the group

The mean age of patients was 29.5 years (from 0.5 to 59.0 years). Patients aged 19–44 years predominated - 115 (77.0%) ***(Fig. 1)***. Most often, a total damage was detected, as well as the damage to the levels of C5-C6-C7 and C5-C6. In 135 (91.0%) patients STI BP was caused by a high-energy closed traction damage to BP without solution of continuity of superficial and deep soft tissue structures of the lateral triangle of the neck (without/ with fracture/osteosynthesis of the clavicle), in the rest it was caused by open damage to structures of BP of the lateral triangle of the neck.

To identify groups of patients according to the classification of D.C. Chuang [5] a simplified approach was used: all closed injuries (excluding damage to the superficial soft tissue and deep structures of the lateral triangle of the neck) STI BP corresponded to level 1, and open injuries to level 2-3. The simplification of the approach is due to the inability to visualize the structures of the BP/cervical spine in the preoperative period using computed tomography (CT) or magnetic resonance imaging (MRI) at the initial stages of the study (2013-2014). Confirmation of level 1 of STI BP according to the Chuang classification significantly influenced the choice of surgical method of recovery in 2014-2018, but not in 2019 (final stage).

The median time from injury to any primary surgery was 7.4 months (from 2 weeks to 6 years). Most patients (105, or 70.0%) underwent primary surgery within 6 months ***(see Fig. 1)***.

Study design was analytical, controlled, retrospective cohort single-centre, conducted in 2013-2019.

Characteristics of surgeries

All surgical procedures performed on patients are divided into two categories: within the new concept - selective reinnervation/nerve transfer (NT), and the old concept - neurolysis and grafting. Detailed methods of surgical interventions (including technical features within the new concept) are presented in numerous publications [3,6].

To facilitate understanding of the process of changing the concept of surgical treatment of traumatic injuries of BP, the analysis was made of the impact of each of the used surgical concepts / methods on the restoration of only the function of flexion in the elbow joint (the highest priority function of the upper limb [7]). Therefore, the results of surgical treatment of only 148 patients (1 case of C5 level STI BP was withdrawn) were used for the final analysis. To restore the function of flexion in the elbow joint, 58 (39.0%) patients underwent NT, 76 (52.0%) - neurolysis of BP structures, 14 (9.0%) - grafting as a primary surgery ***(Table 1)***. There was no blind selection of patients for any primary surgery. The choice of a more aggressive surgical approach was based on the willingness of the performers to use it in a particular case of STI BP at different periods of the study.

Among 58 patients, who underwent NT as a primary surgical intervention, was performed, selective reinnervation of branches to *m.biceps brachii* (BB) or non-selective reinnervation (with extraction of branches to m.coracobrachialis from the coaptation zone of the nerve donor and *n.musculocutaneus),* extraplexus nerve donor (e-ND) were used in 35 (non-selective NT) ***(Fig. 2)***, intraplexus nerve donor (i-ND) in 23 (both selective

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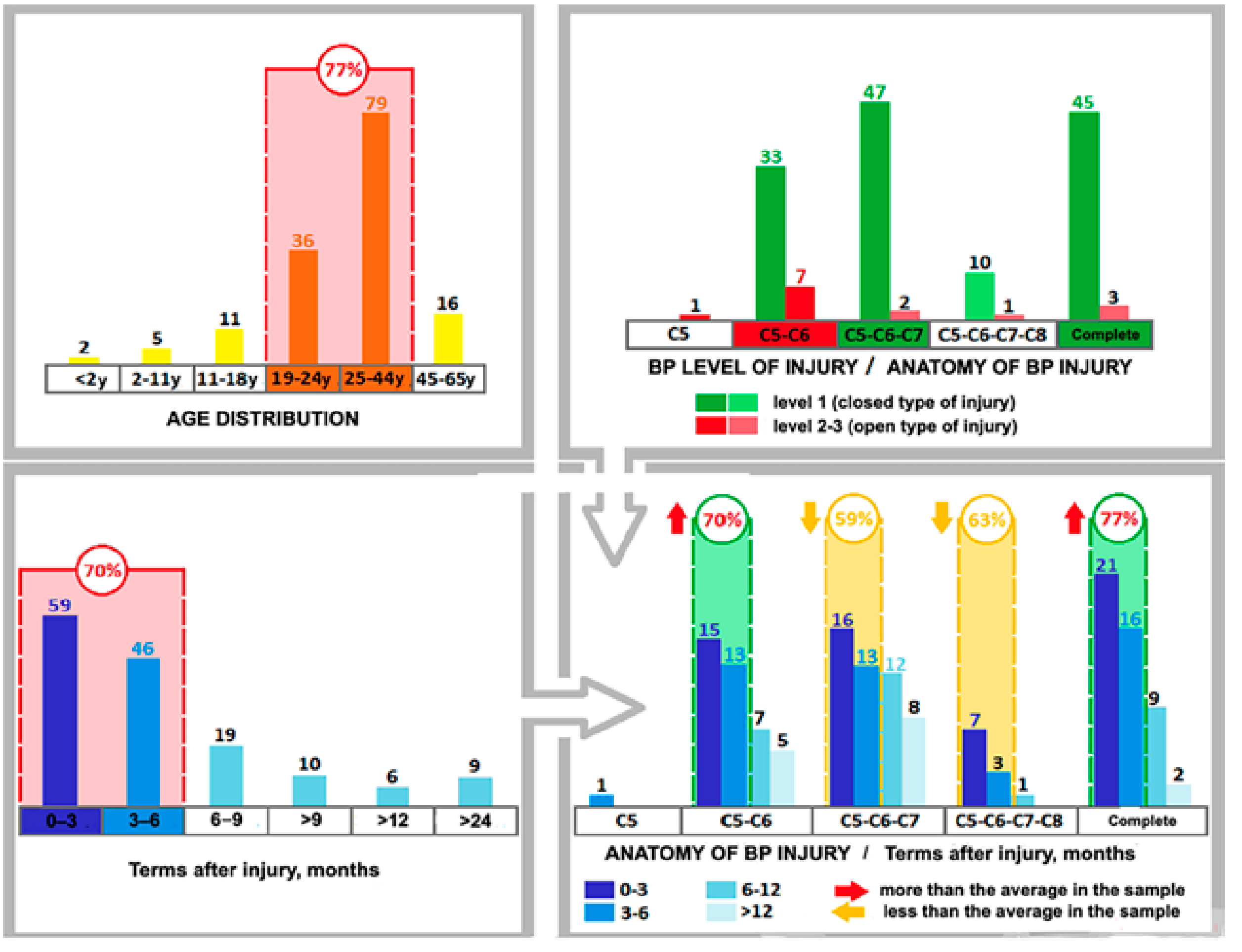

Fig. 1. Distribution of patients by age, anatomy of injury, period after injury: BP - brachial plexus

and non-selective NT). The choice of nerve donors (ND) was most influenced by the anatomy of BP injury.

The criteria for selecting ND at the presurgical stage were clinical (neurological examination), radiological (diaphragm relaxation) and electrophysiological (preoperative electroneuromyography (ENMG), intraoperative diagnostic direct stimulation according to standard technique) data on the preservation of nerve function, that could potentially be ND. Of the 26 patients with STI BP of total type who underwent NT, e-ND was used in 25 in the absence of the function of any other i-ND ***(see Fig. 2)***. In 6 cases, in the absence of n.phrenicus (PhN) function, other e-NDs were used ***(see Fig. 2)***: in 2 - motor portions of intercostal nerves 3-4-5 (ICN), in 4 - different branches of n.accessorius (Acc). In 8 out of 9 cases using n.pectoralis lateralis (Pect (L)), in 2 out of 7 cases using n.ulnaris fibers to m.flexor carpi ulnaris (UN (FCU)), in 4 out of 7 cases using n.pectoralis medialis (Pect (M)) as i-ND the cranial spread of STI BP was verified, accompanied by the absence of PhN function (not available as e-ND) ***(see Fig. 2)***. Data on the timing of primary surgery are shown in ***Fig. 2***. Only two i-NDs (n.pectoralis lateralis and n.pectoralis medialis) were used for NT in less than 6 months from the moment of STI BP in 44.0 and 43.0% cases (less than the average in the sample), others, both i-ND and e-ND, in less than 6 months (from 72.0 to 100.0% cases), i.e. more than the sample average.

Table 1. Distribution by primary surgical interventions used in the study, depending on the level of injury

Injury level	N	G	NT
C5-6	19 (25,0%)	6 (42,9%)	15 (25,9%)
C5-6-7	30 (39,5%)	2 (14,2%)	17 (29,3%)
C5-6-7-8	10 (13,2%)	0	1 (1,7%)
Total	17 (22,3%)	6 (42,9%)	25 (43,1%)

Note: N – neurolysis; G – grafting; NT – nerve transfer

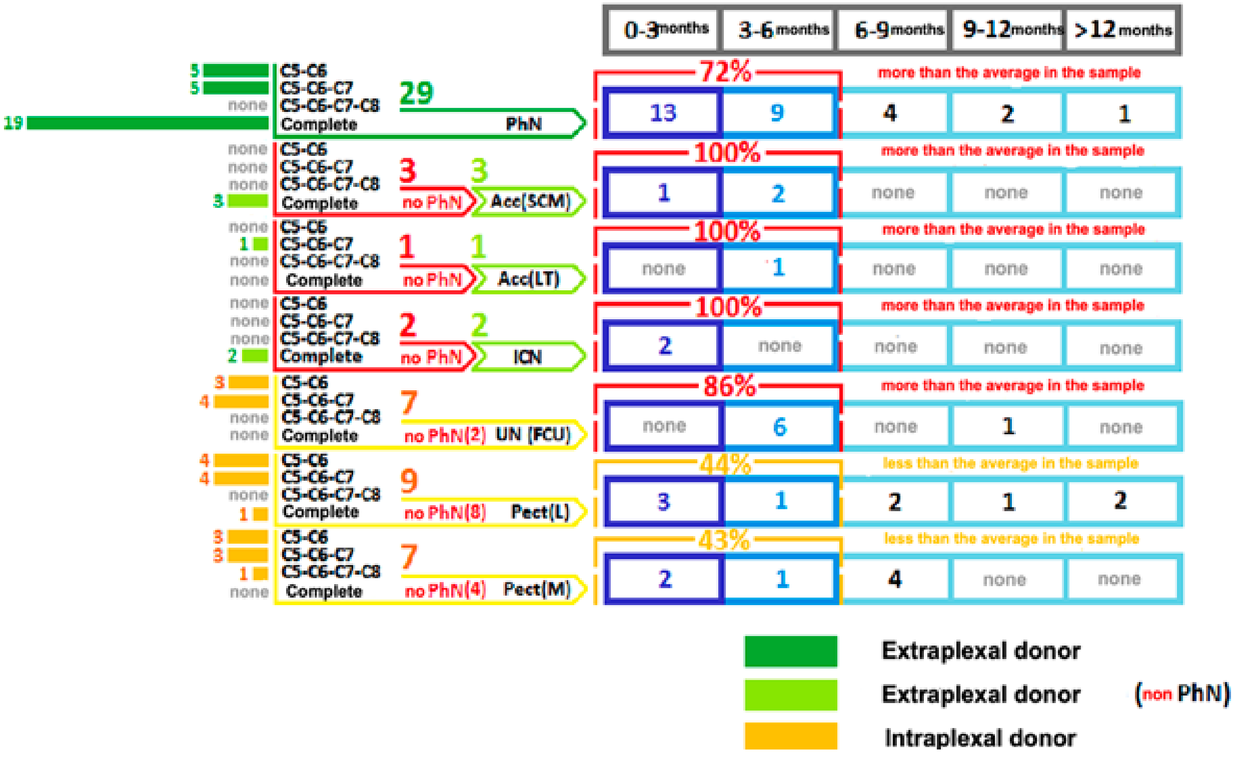

Fig. 2. Used motor nerve donors depending on the anatomical characteristics of supraclavicular traumatic injuries of the brachial plexus:
Acc (SCM) - pars sternocleidomastoideus nervi accessorii; Acc (LT) - pars trapezoideus (to pars ascendens m.trapezius) nervi accessorii; ICN - motor portions of intercostal nerves 3-5; no PhN - cranial spread of STI BP, PhN does not work; w / a - was absent; * - any number means the number of cases of using any motor nerve donor

Evaluation of results

All patients were instructed to restore motor function and adhere to standardized rehabilitation programs 3 months after any primary surgery. Rehabilitation programs after the use of neurolysis and grafting were aimed at maintaining the mobility of the joints of the upper limb within the maximum natural range of motion. All patients after neurolysis and grafting underwent the neurological examination, supplemented by electrophysiological examination (ENMG) according to a standard method 6, 9 and 12 months after a primary surgery. If BB reinnervation did not occur (M0 on the MRC scale) or reinnervation was ineffective (M2-3), the possibilities of orthopedic corrective interventions (transposition of the tendon-muscle complex / complexes) were used, but not earlier than 15 months after a primary surgery.

Rehabilitation programs after NT were designed and carried out depending on the specific functions that were originally provided by ND. Patients were instructed on the need to perform specific motor exercises both under the supervision of a rehabilitation physician and independently at home.

The waiting period for primary signs of reinnervation, accompanied by active contractile function of BB, regardless of its strength on the MRC scale, differed i-ND and e-ND.

The period (during the entire patient follow-up period) allocated for the BB reinnervation was 9 months when performing NT with involvement of i-ND and 12 months with involvement of e-ND. All patients underwent neurological examination 9, 12 and 15 months after NT, supplemented by electrophysiological examination (ENMG) according to the standard method. If BB reinnervation did not occur (M0) or reinnervation was ineffective (M2-3), then the possibilities of orthopedic corrective interventions (transposition of the tendon-muscle complex/complexes) were used, but not earlier than 17 months after a primary surgery.

The primary purpose of the neurological examination was to assess the recovery of effective power of BB on the MRC scale [8]. Functional recovery of BB to M4-5 was considered the recovery of effective power (Ep). The functional effective power of BB (Ef) was assessed by measuring the change in the angle during bending in the elbow joint up to a maximum value of 121° (maximum required). Angular characteristics are based on the requirements for elbow flexion during most vigorous daily activities (81–121°) [9].

Needle and superficial ENMG were mainly used in the early (9 and 12 months after neurolysis and grafting) and late (15 and 17 months after NT) periods to confirm ineffective reinnervation or the absence of BB reinnervation. In such cases, orthopedic corrective interventions (transposition of the tendon-muscle complex/complexes) were recommended to restore elbow flexion, if possible.

None of the patients who underwent neurolysis or grafting as a primary surgery underwent NT at later stages of the study at the follow-up period specific to these primary surgeries (6–15 months).

Statistical analysis

There were limitations of the study when conducting statistical data processing: significant heterogeneity of characteristics (age, gender, terms of injury, etc.) of patients did not allow the formation of groups according to similar characteristics for meaningful statistical analysis.

Results and discussion

According to E. Martin et al. [10], most nerve transfers in BP injury are effective if performed no later than 6 months after injury, with a clear tendency to decrease their effectiveness as the period after injury increases [10], therefore all the results of recovery of BB function were analyzed taking this into account.

Neurolysis as a primary surgery was performed for up to 6 months in 51 patients out of 76. About 23.5% of patients had recovery of effective power of BB (M4-5),10.0% - had ineffective reinnervation (M2-3), in 66.5% there was no reinnervation of BB (M0). -1) ***(Fig. 3)***. Of the 25 patients who underwent neurolysis as a primary surgery later than 6 months after STI BP, only 8.0% had recovery of effective power of BB (M4-5), while 4.0% - had ineffective reinnervation (M2-3), in 88.0% - the absence of reinnervation of BB (M0-1). The ratio for effective spontaneous recovery of effective power of BB after a primary surgery (neurolysis) for up to 6 months is 1:3, and in general - 1:4 regardless of the timing of a primary surgery (neurolysis).

Grafting as a primary surgery was performed for up to 6 months after STI BP in 12 patients out of 14. About 33.0% of patients had recovery of effective power of BB (M4-5), in 8.0% - ineffective reinnervation (M2-3), in 59.0% - the absence of reinnervation of BB (M0-1) ***(see Fig. 3)***. None of the 2 patients who underwent grafting after 6 months as a primary surgery had reinnervation of BB (M0-1). The ratio of recovery of effective power of BB after performing grafting as the primary surgical intervention is 1: 4, regardless of the timing of its implementation.

Nerve transfer as a primary surgery was performed for up to 6 months after STI BP in 41 patients out of 58. About 71.0% of patients had a recovery of effective power of BB (M4-5), in 5.0% - ineffective reinnervation (M2-3), in 24.0% - the absence of BB reinnervation (M0-1) ***(see Fig. 3)***. Of 17 patients who underwent NT as a primary surgery 6 months after STI BP, 59.0% reported an effective recovery of BB power (M4-5), 6.0% had ineffective reinnervation (M2-3), and in 35.0% the absence of BB reinnervation (M0-1). The ratio of chances of effective recovery of BB power after performing as a primary surgery of NT for up to 6 months is 2.4:1.0, and in general - 2:1, regardless of the timing of implementation as a primary surgery of NT.

Conclusion: the results of surgical interventions within the new (selective reinnervation /nerve transfer) and old (neurolysis and grafting) concept of recovery of *BB* effective power *irrespective the time of their implementation indicate the advantage of NT over the methods of "internal" control group neurolysis and grafting): respectively 67.0 and 20.0% recovery of effective power to M4-5.*

In 28 (68.0%) cases of using NT as a primary surgery for up to 6 months after STI BP, only e-NDs were used with an overall efficiency of 75.0% in recovery of the effective power of BB to M4-5. Most of positive results were associated with the use of PhN with an overall efficiency of 91.0% ***(Fig. 4)***. Other e-NDs showed a generally poor efficiency (17.0%).

In 13 (32.0%) cases of NT performed as a primary surgery for up to 6 months after STI BP, only i-NDs were

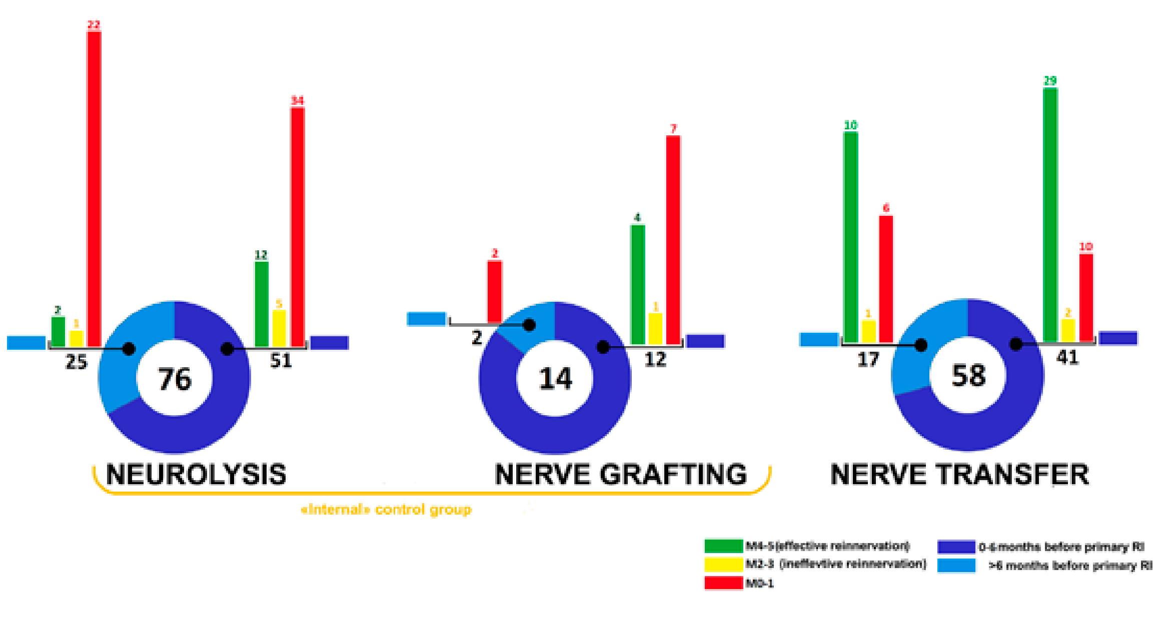

Fig. 3. Effectiveness of recovery of effective power of m.biceps brachii after performing various types of primary surgical interventions for up to 6 months and later after supraclavicular traumatic injuries of the brachial plexus: SR – surgical repair

used with an overall efficiency of 61.5% to restore the effective power of BB to M4-5. Most of the positive results were associated with the use of UN (FCU) with an overall efficiency of 83.0% ***(see Fig. 4)***. Other e-NDs showed an efficiency of about 43.0%.

In 7 (41.0%) cases, of using NT as a primary surgery for more than 6 months after STI BP only e-NDs, namely PhN, was used with an overall efficiency of 71.0% to restore the effective power of BB to M4-5 ***(see Fig. 4)***.

In 10 (59.0%) cases of using NT as a primary surgery for up to 6 months after STI BP, only i-ND was used with an overall efficiency of 50.0% to restore the effectve power of BB to M4-5. Most of the positive results were associated with the use of Pect (M) with an overall efficiency of 86.0% ***(see Fig. 4)***. Other e-NDs showed an efficiency of about 17.0%.

Conclusion: changes in the profile of e-NDs and i-NDs use depending on the time of implementation as a primary surgical intervention of NT: with the predominant use of e-NDs for up to 6 months (68.0% compared to 32.0% of cases of i-NDs) and i-NDs after 6 months (59.0 and 41.0% of cases).

Of 14 patients (18.0% of 76) who showed recovery of effective power of BB to M4-5 after neurolysis as a primary surgery, regardless of the time after STI BP, effective recovery of the function was achieved in only 9 (64.0%) ***(Fig. 5)***.

Of 4 cases (29.0% of 14 patients) recovery of effective power of BB to M4-5 after performing grafting as a primary surgery, regardless of the time after STI BP, effective recovery of the function was not achieved in any case ***(see Fig. 5)***.

Of 39 patients (67.0% of 58) recovery of effective power of BB to M4-5 after performing NT as a primary surgery, regardless of the time after STI BP, effective recovery of the function was achieved only in 15 (38.5%) ***(see Fig. 5)***.

Regardless of the period after STI BP, recovery of effective power of BB to M4-5 after NT using PhN as a primary surgical intervention was achieved in 86.0% of cases, and effective recovery of function was achieved only in 36.0%. The use of PhN for up to 6 months made it possible to restore the effective function of BB in 40% of cases, and the use after 6 months - only in 25.0% ***(see Fig. 4)***.

Recovery of effective power of BB to M4-5 after performing NT as a primary surgery using Pect (L) regardless of the time after STI BP, was achieved in 22.0% of cases, and effective recovery of the function was achieved in 50.0% of cases. The use of Pect (L) for up to 6 months allowed to restore the effective function of BB in 0% of cases, after 6 months - in 100.0% of cases ***(see Fig. 4)***.

Regardless of the time after STI BP, recovery of effective power of BB to M4-5 after performing NT as a primary surgery using Pect (M) was achieved in 86.0% of cases, and effective recovery of function - in 33.0%. The use of Pect (M) for up to 6 months allowed to restore the effective function of BB in 100.0% of cases, after 6 months - in 0% ***(see Fig. 4)***.

Recovery of effective power of BB to M4-5 after performing as a primary surgery using UN (FCU) was achieved in 71.0% of cases, and effective recovery of function - in 60.0% for up to 6 months ***(see Fig. 4)***.

Conclusions: e-ND Pect (M) and UN (FCU) have the greatest potential for recovery of effective BB *function in terms of up to 6 months - 100.0 and 77.0%, respectively. The decrease in the potential for recovery of effective function of i-ND PhN as the period after STI BP increases is associated with the peculiarity of the technical component of its use, namely the distance between ND and BB (is overcome by autologous nerve graft) and, accordingly with the timing of expected muscle regeneration/degeneration. The high potential for recovery of effective e-ND function of Pect (L) after 6 months is associated with the formation of a clear clinical and electrophysiological picture, indicating preserved or restored function of Pect (L) itself, which can be masked*

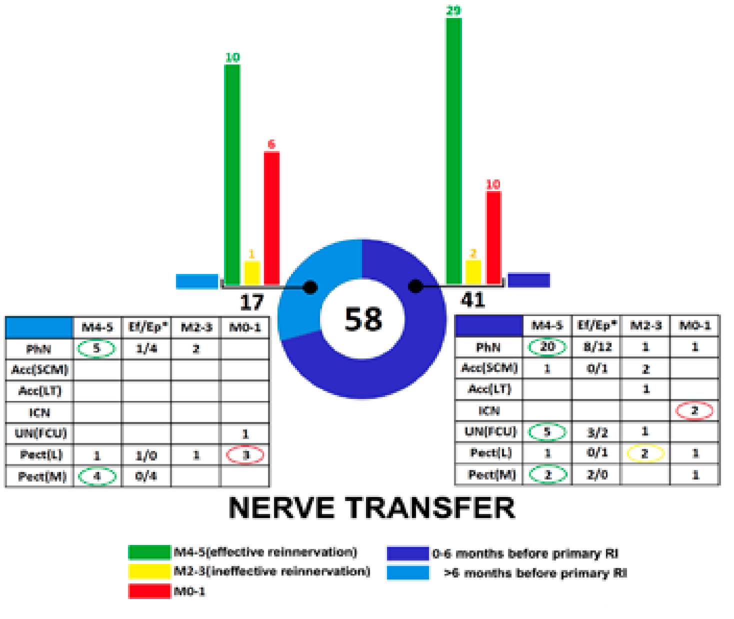

Fig. 4. Efficiency of recovery of effective power of m. biceps brachii as a result of nerve transfer using donor nerves of extra- and intraplexus origin for up to 6 months and later 6 months after supraclavicular traumatic injuries of the brachial plexus: SR – surgical repair; Ep - effective power of the muscle; Ef - effective muscle function

by preserved Pect (M) function at an earlier terms after STI BP.

If 148 patients are retrospectively divided into two groups according to the main feature - the number of surgeries performed within the new concept (NT), then it can be claimed that for the treatment of patients in group A (n = 102) surgeons-specialists of one permanent team during 2013-2019 gradually began to use only NT. Group B patients (n = 46) were treated by surgeons-specialists of another permanent team during 2013-2019 and was not accompanied only by the use of NT within the new concept of surgical treatment of BP injuries. Both teams of surgeons-specialists worked in the same department.

The use of a new concept of surgical treatment of BP injuries in patients of group A was characterized by a sinusoidal type of increase in the number of cases of its use throughout the study period. Thus, in 2013-2016, the number of cases of NT use increased from 31.0 to 73.0% ***(Fig. 6)***. In 2014-2015, there was a change in the number of cases of the surgical method within the old concept (neurolysis) and NT - 9:7 and 4:12. Accordingly, the frequency of using the surgical method within the old concept decreased from 58.0 to 20.0% ***(see Fig. 6)***.

The frequency of NT use continued to increase until the end of 2017, and during 2017-2018 it decreased from 62 to 54.0%, in 2019 the frequency of NT use was 100.0% ***(see Fig. 6)***.

Treatment of patients in group B was mainly based on the use of surgical methods within the old concept (neurolysis or grafting). The frequency of their use during the study period was 71.0–88.0% and 12.0–29.0%, respectively ***(see Fig. 6)***. The refusal to use NT within the new concept of surgical treatment in patients of group B in 2017 was due to the poor efficiency of the method (33.0%) in 2015-2016.

Conclusions: for one of the teams of surgeons-specialists (group A) there was a change in the concept of surgical treatment of BP injuries. The refusal to continue using the surgical method of nerve transfer in patients of group B was accompanied by its poor efficiency at initial stages of the introduction of the new concept.

The sinusoidal type of increase in cases of NT use within the new concept of surgical treatment of BP injuries in patients of group A has a logical explanation. The process of adopting the new concept involved familiarization with the basic principles (2013-2014) and limited use of certain techniques (end of 2015). The process itself required only a simple replacement of the method of neurolysis or grafting (within the old concept) with the NT method (within the new concept). The positive results obtained at the initial stages of the study (2013–2014) when using NT ***(Fig. 7)*** were replaced by the predominance of negative results in 2015 against the background of an increase in the number of cases of NT use in general. Replacing one method with another no longer gave the desired result, it became necessary to clearly define the limits of productive use of the method, answering the question of how, when and what to do using the new concept of surgical treatment in an individual case of BP injury, that is, the stage of formation of the method began, lasting until 2019.

The NT method was formed within the new concept by determining the influence of four main factors ***(Table 2)***: the anatomy of BP injury ***(factor 1)***, which, as it became known during the study, influenced the effectiveness of the method in general and the possibility of using ND with preserved function ***(factor 2)***, the period from BP injury to the primary surgical intervention using the NT method ***(factor 3)***, radiological data (CT/MRI of BP / cervical spine) examination methods ***(factor 4)***, which determined the need for more aggressive surgical approach (use of NT) at the stage of planning surgery or neurolysis / grafting.

Factor 1 (anatomy of injury). At the initial stages of the study (2013), NT was mainly used for partial variants of STI BP in 83% of cases. During 2014–2015, with the wider introduction of the NT method into daily surgical practice, the frequency of total variants of STI BP treated with the NT method increased to 57.0% ***(see Fig. 6)***. As a result of the change in the injury profile of BP, the number of different types of applied ND during 2013-2015 increased from 2 to 5 ***(see Fig. 7)***. The increase in the

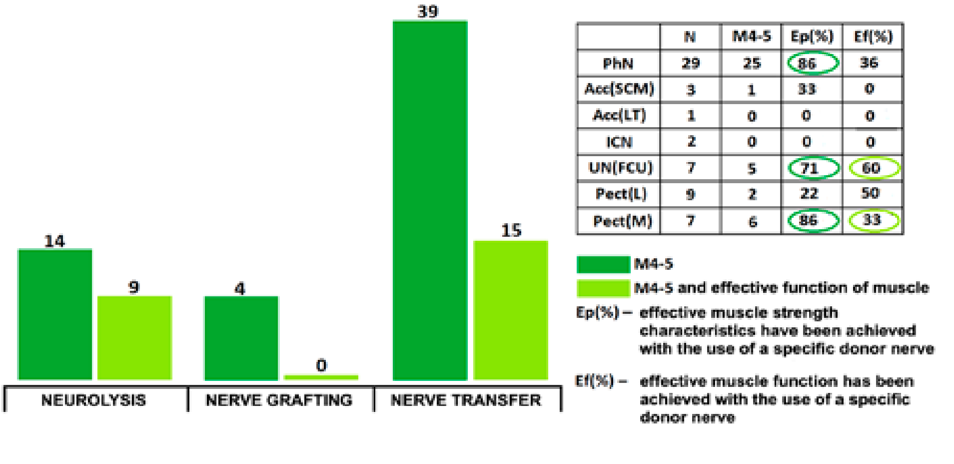

Fig. 5. Comparison of recovery of effective power and effective function of m.biceps brachii as a result of various types of primary surgeries regardless of the time after supraclavicular traumatic injuries of the brachial plexus

number of NDs used in 2015 resulted in a sharp decrease in the efficiency of the NT method from 100.0% in 2014 to 42.0% in 2015 ***(see Fig. 7).***

*Conclusion: despite the increase in the absolute number of surgeries performed under the new concept during 2013-2015 (11:6, 9:7 and 4:12 for neurolysis / nerve transfer), the decrease in the effectiveness of the method to 42.0% is associated with an incomplete process of determining reliable NDs **(factor 2).***

Factor 2 (choice of ND). At the end of 2017, the process of creation a pool of reliable NDs was completed ***(Fig. 8)***. Not accounting for the results of the use of ND "despair" - an average efficiency of 33.0% (their involvement is associated with the inability to use other ipsilateral NDs in the surgical treatment of all total variants of STI BP) ***(see Fig. 8)***, a pool of reliable ipsilateral e-NDs and i-NDs looked like this: PhN, Pect (M) and UN (FCU). Withdrawal of Pect (L) from the pool of reliable NDs is due to the generally low efficiency (22.0%) in 2013-2017 ***(see Fig. 7 and 8)***.

Conclusion: despite the creation of a pool of reliable ND during 2013-2017, their use was not always accompanied by the recovery of particularly effective power of BB, which is associated with the influence of factor 3.

Factor 3 (terms before NT). Since the terms of the effective use of NT were fixed rather quickly (consulting about 70% of patients for up to 6 months ***(see Fig. 1.)***) - during 2013-2014, the effectiveness of the surgical method within the new concept increased to 100.0 % ***(see Fig. 7)***. In addition, the time limits set at the initial stages of the study led to limited use of a certain number of reliable NDs, especially in the case of cranial spread of STI BP and the absence of PhN function ***(see Fig. 2)***. Thus, the use of Pect (M) made it possible to extend the time limits of use of i-NDs to 9 months with an efficiency of 100.0%. This statement partially also applies to the use of e-NDs, namely PhN, with an efficiency of up to 71.0% 6-9 months after STI BP ***(see Fig. 4)***.

Conclusion: the extension of time limits for performing NT contributed to an increase in the pool of effective NDs due to the later consultations (up to 9 months) of patients with a certain anatomy of STI BP *(C5-C6 and C5-C6-C7)* ***(see Fig. 2)****, which, in our opinion, is associated with the peculiarity of BP injury.*

Factor 4 (radiological criteria). Expansion of indications for the use of less aggressive approach within the old concept of surgical treatment of STI BP, namely neurolysis of BP, which was associated with the introduction of radiological selection criteria (CT/MRI data without clear signs or with doubtful signs of avulsion) of patients at the presurgical stage, contributed to a significant improvement of the results

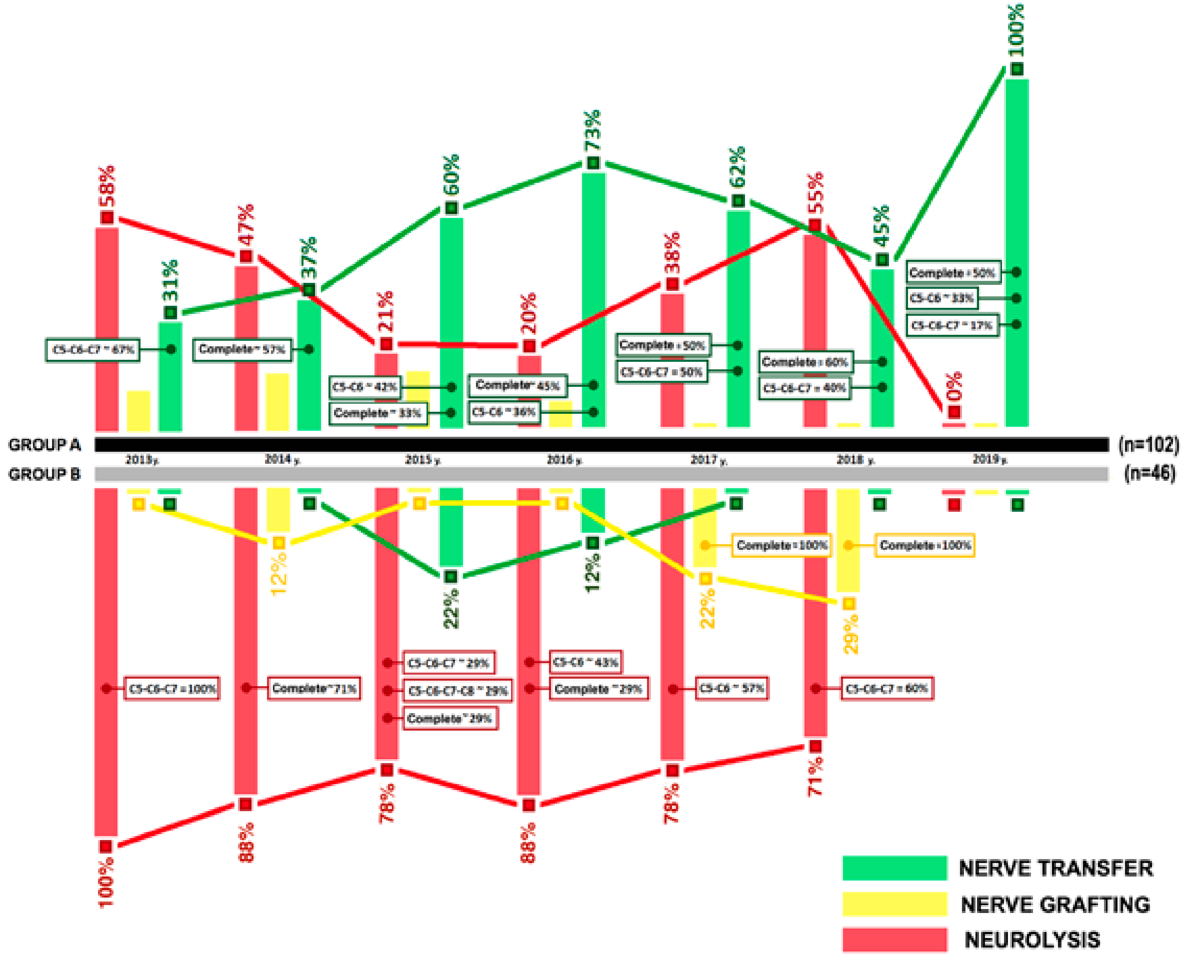

Fig. 6. Dynamics of the use of different surgical methods in patients of groups A and B during the study period

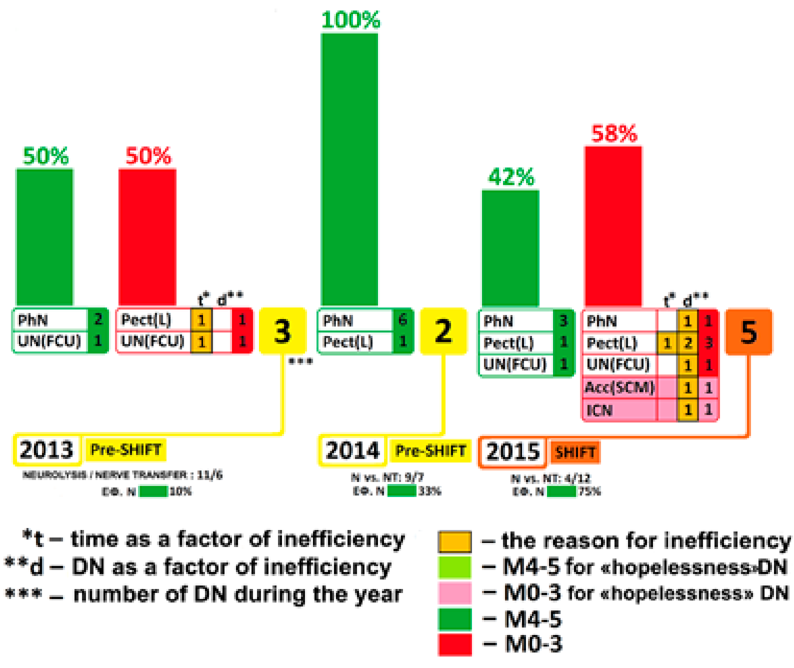

Fig. 7. Correlation between the efficiency of m.biceps brachii reinnervation, donor nerves and the terms of their use, the efficiency of brachial plexus neurolysis in 2013-2015:
pre-SHIFT - years during which there was no increase in the absolute number of nerve transfers in the structure of surgical treatment of STI BP (before the concept was changed); SHIFT - the year during which there was an increase in the absolute number of nerve transfers in the structure of surgical treatment of STI BP (strategy changes); N - neurolysis; NT – nerve transfer; ef. N - annual efficiency of neurolysis; N vs. NT - annual ratio of N and NT

Table 2. Changes in the effectiveness of nerve transfer and the evolution of the main factors influencing its effectiveness

Factor	Evolution of factors	Changing the recovery efficiency
1	Change profile	Decreased efficiency
2	Increasing the number of ND	Decreased efficiency
	Installation of reliable ND	Increased efficiency
3	Time limit	Decrease of ND ⇒ decreased efficiency
	Extension of the term	Increase of ND ⇒ increased efficiency
4	Expansion of indications for neurolysis	Decreased efficiency
	Refusal of radiological criteria	Increasing the amount of NT⇒ Increasing efficiency

of neurolysis in 2013-2015 ***(see Fig. 7)*** - from 10.0 to 75.0% efficiency. Accordingly, the application of primary effective radiological criteria entailed a temporary change in surgical approach towards a wider use of neurolysis within the old surgical concept in 2016-2018 ***(see Fig. 8)***. It was the introduction of criteria based on the data of radiological examination methods has led to the formation of a sinusoidal type of the curve of the use of nerve tranfer method ***(see Fig. 6)***. The increase in the number of patients in whom radiological selection criteria for neurolysis were used led to a progressive decrease in the efficiency of neurolysis from 75.0% in 2015 to 0% in 2018 ***(see Fig. 8)***.

Conclusions: the use of radiological criteria for the selection of patients for performing neurolysis in STI BP *is not a reliable method for ensuring effective recovery of function. Taking into account factors 1–3 when using the method of nerve transfer within the new concept of surgical treatment of BP injuries made it possible to increase the recovery of effective power of BB to 100.0% in 2019.*

Conclusions

1. Adoption of nerve transfer within the new concept of surgical treatment of brachial plexus injuries occurred only in one group of surgeons-specialists of one department. The adoption process lasted during 2013–2019 and was presented in 3 phases: familiarization with the basic principles and limited use of selective techniques during 2013–2014, defining the limits of productive use of nerve transfer and studying the impact of four main factors (anatomy of injury, post-injury time, the choice of donor nerves, the reliability of auxiliary radiological diagnostic methods) during 2015–2018, the adoption of nerve transfer as the main method of surgical treatment of brachial plexus injuries.

2. Ensuring the clinical effectiveness of nerve transfer within the new concept of surgical treatment of brachial plexus injuries at the level of 100.0% is achieved by taking into account the influence of four main factors (anatomy of injury, post-injury time, the choice of donor nerves, radiological diagnostic criteria).

3. The most effective donor nerves, taking into account the anatomical characteristics of supraclavicular traumatic injuries of brachial plexus are n.phrenicus, n.pectoralis medialis and fibers to m.flexor carpi ulnaris in the n.ulnaris structure.

4. The optimal time for nerve transfer is 3–9 months after the injury, taking into account the anatomical characteristics of supraclavicular traumatic injuries of brachial plexus.

5. Radiological criteria for examining a patient at the presurgical stage can not be a decisive factor in choosing a surgical method of treatment of supraclavicular traumatic injuries of brachial plexus.

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 each patient.

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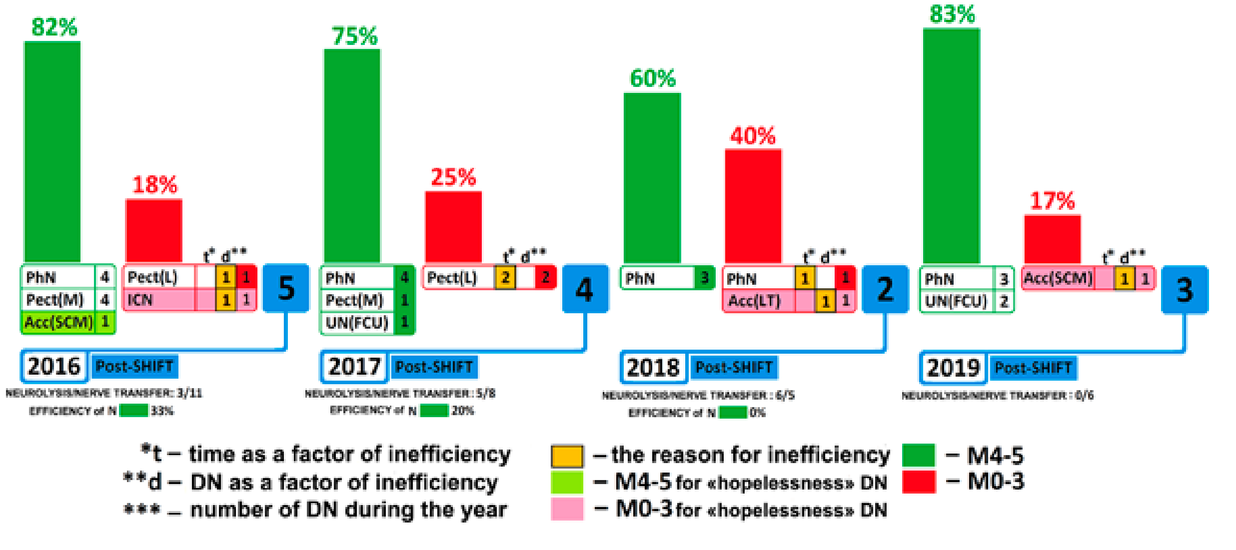

Fig. 8. Correlation between the effectiveness of reinnervation of m.biceps brachii, donor nerves and the timing of their use, the effectiveness of brachial plexus neurolysis in 2016–2019:
post-SHIFT - years during which the formation and change of the concept of surgical treatment of STI BP was noted; efficiency N - annual efficiency of neurolysis; Acc (SCM) - pars sternocleidomastoideus nervi accessorii; Acc (LT) - pars trapezoideus (to pars ascendens m.trapezius) nervi accessorii; ICN - intercostal nerves 3-5.

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