LITERATURE REVIEW

Motor nerve transfers for restoration of upper arm function in adult brachial plexus injuries- basics, advantages, problems and strategies

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Abstract

Introduction: Nerve transfers are the only surgical option for reconstruction of directly irreparable injuries of the brachial plexus. In the recent years, there has been a trend toward the increased use of nerve transfers, with the introduction of new methods and novel indications. Patients with total brachial plexus palsy generally have poor outcomes due to the limited number of donor nerves. On the contrary, patients with partial injuries involving the C5, C6, and sometimes C7 spinal nerves have favorable outcomes in a large majority of cases. In both situations, restoration of elbow flexion and shoulder functions are the main priorities. The purpose of this review article to characterize the advantages, problems and controversies of nerve transfers.

Methods: PubMed/Medline database was searched for English-language original research and series of adult patients who received nerve transfers for functional restoration of the upper arm, performed within one year after injury and with minimum follow-up of one year. Literature search for outcome analysis was limited to articles published after 1990, amounting to 45 systematic reviews / meta-analyses of the most common nerve transfers (intercostal, spinal accessory, fascicular, and collateral branches of the brachial plexus). Analysis of clinical outcomes was based on Medical Research Council (MRC) grading system for muscle strength, and grades M3 or more were considered as useful functional recovery.

Results: A total of 70 articles were included. Generally, intraplexal nerve transfers resulted in a higher rate and better quality of recovery compared to extraspinal transfers. Grades M3 or higher were obtained in 72% of the intercostal and 73% of the spinal accessory nerve transfers for restoration of elbow flexion, and in 56% vs. 98% of transfers for restoration of shoulder function. Among intraplexal nerve transfers, elbow flexion was restored in 84% to 91% of the medial pectoral, 100% of the thoracodorsal, and 94% to 100% of the single or double fascicular nerve transfers. Shoulder function was restored in 81,8% of the medial pectoral, 86% to 93% of the thoracodorsal, and 100% of the triceps branch nerve transfers. Dual nerve transfer (simultaneous reinnervation of the suprascapular and axillary nerves), resulted in 100% rate of recovery.

Conclusion: Double fascicular transfer for restoration of elbow flexion and dual nerve transfer for restoration of shoulder function resulted in the most favorable results relative to other transfers, especially regarding quality of recovery. Medial pectoral and thoracodorsal nerve transfers were reasonable alternatives for restoration of both functions.

Keywords: brachial plexus; closed injury; donor nerve; functional priority; nerve transfer; recipient nerve.

Introduction

Nerve transfer or neurotization involve reinnervation of the distal denervated, functionally important arm nerves using intact expendable nerves as donors. A variety of donor nerves, extraplexal or intraplexal, have been used with varying efficacy.

The history of nerve transfers dates back over 100 years. The first report, published by Tuttle in 1913, involved use of the spinal accessory nerve and elements of the cervical plexus as donors. Thereafter, there were only few reports concerning mainly intraplexal procedures in neurotization of the axillary and/or musculocutaneous nerve. In 1920, Vulpius and Stoffel published on the use of the brachial plexus branches to the pectoral muscles as donors. In 1929, Foerster reported nerve transfer using the branches to the latissimus dorsi and subscapular muscles. Finally, in 1948, Lurja reported the use of the pectoral and thoracodorsal nerves in repair of the upper trunk injuries[1,2]. Seddon, in 1963, reanimated nerve transfer procedures, publishing the use of the third and fourth intercostal nerves in reinnervation of the musculocutaneous nerve[3]. Pioneers in modern reconstructive surgery of the brachial plexus injuries – Aligmantas Narakas, Hanno Millesi and Yves Alnot – generated significant enthusiasm in 1970s and 1980s. They introduced, along with several other authors, numerous innovative techniques. The main goal was reinnervation of the upper arm nerves and restoration of their functions, including elbow flexion, shoulder abduction and external rotation.

Extraplexal transfers included the spinal accessory nerve[4,5,6,7], anterior branches of the cervical plexus[8], phrenic nerve[9], contralateral C7 spinal nerve[10] and upper intercostal nerves[11,12,13] as donors. These transfers were predominantly performed in patients with total brachial plexus palsy. Most intraplexal transfers was introduced during the last two decades of the 20th century. The advent of this modern era of nerve transfers occurred as series of studies explored new possibilities in this field. These nerve transfers included the use of the medial pectoral[15,16,17,18,19], thoracodorsal[15,17,19,20,21], fascicles of the ulnar and median nerves[22,23,24,25,26] and triceps branches of the radial nerve[17,28] as donors. These nerves are available for transfer in cases with upper brachial plexus palsy involving the C5 and C6 spinal nerves, with or without involvement of the C7. A complete or near complete recovery is expected.

Indications for motor nerve transfers and the patient population who may benefit from such operations continue to expand. The first indications were directly irreparable traction injuries of the brachial plexus with cervical spinal root avulsion or high intraforaminal spinal nerve injuries[29]. Thereafter, indications were significantly extended including[30,31,32]:

1. Extensive longitudinal nerve defects
2. Extensive neuroma in continuity
3. Injury to several nerve elements at different levels
4. Partial nerve injuries with clearly defined neurological deficit in one part of the plexus
5. Injuries to one nerve element at several levels
6. Associated vascular and significant bone injuries
7. Significant scarring at the site of injury
8. Surgery delayed for more than 12 months

In elderly patients and those with unsuccessful previous direct nerve repair, nerve transfers may be used as well.

Novel indications for nerve transfers with initial success and expected validation in the future:

1. Spinal cord injuries since these patients have intact lower motor neurons below the level of injury with preserved connection to the target muscles[33,34,35]
2. Radiation-induced brachial plexopathy[36]
3. Parsonage-Turner syndrome[37,38]
4. Contralateral C7 spinal nerve transfer in patients with chronic stroke for motor improvement and reduction of spasticity[39]

An ideal timing for nerve transfer has not been yet established. However, it is widely accepted that surgery should be done in a period between 3 and 5 months after injury if there are neither clinical nor electromyographic signs of recovery[29,30,31]. Target muscle should be reinnervated between 12 and 18 months in order to prevent muscle atrophy and loss of the motor end plates. The presence of fibrillation potentials after this period is an indication that denervated muscle is still viable. Regardless, some authors do not recommend surgery after postinjury period of 9 months. The recommended timing is different for special cases. The proposed timing of surgery for radiation-induced brachial plexitis and Parsonage-Turner syndrome is between 6 and 9 months, if there is no signs of recovery[37]. In patients with spinal cord injury or chronic stroke there is no time limit because of preserved lower motor neurons[34]. Contraindications for nerve transfer are rare and include presence of a superior reconstructive option, excessive surgical delay (>18 months), and muscle strength in the donor innervation zone of less than Medical Research Council (MRC) grade 4.

The purpose of this review article is to characterize the advantages, problems and controversies of nerve transfers and derive some guiding recommendations on their use in brachial plexus reconstructive surgery, for restoration of upper arm motor functions.

Methods

This is a literature review with comparative analysis of the upper arm functions recovery following the most common extraplexal (spinal accessory and intercostal nerves) and intraplexal (single or double fascicular, thoracodorsal, medial pectoral and triceps branches of the radial nerve) nerve transfers.

The PubMed/Medline database was searched for English-language articles containing the MeSH terms "brachial plexus" in conjuction with words "injury" or "trauma" and "nerve transfer" in the title.

Inclusion criteria

1. closed brachial plexus injury
2. upper, extended upper or total brachial plexus palsy
3. timing of surgery less than 12 months after injury
4. follow-up period at least 12 months
5. ≥ 6 cases

Exclusion criteria

1. obstetric brachial plexus palsy

2. peripheral nerve injuries to the axillary and/or musculocutaneous nerve

3. patients older than 65 years

4. combined nerve transfer with nerve grafting

5. combined nerve and tendon transfers

The query returned 680 articles, 70 of which fulfilled the inclusion and exclusion criteria, and were included in this review. In addition to the original research papers, 45 systematic reviews / meta-analyses published after 1990 were selected for statistical analysis. p value of 0.05 or less with the use of Pearson's Chi square, Fisher, ANOVA and Mann-Whitney test was considered as significant.

Analyses used recipient nerves (musculocutaneous, axillary and suprascapular) as dependent variables and donor nerves as independent variables. The significance of the other independent variables such as patient's age and timing of surgery was not extracted.

Grades of M3 or higher on the MRC Manual Muscle Testing Scale were considered useful functional recovery and grades M4 or M5 as a higher quality of recovery for elbow flexion and shoulder abduction.

Review

Advantages of nerve transfers

Motor nerve transfers have several advantages over nerve repair[29,30,31]:

1. Possibility for direct nerve anastomosis in the majority of intraplexal nerve transfers, avoiding interposition of nonvascularized nerve graft with an average of 30% of additional axonal loss across the second suture line.

2. Anastomosis closer to the target muscle where the number of nerve fibers in a recipient

3. nerve is lower and a distal dissection enables separation of the sensory nerve fibers.

4. Shorter distance and time span for regeneration, with an earlier reinnervation

5. Surgery outside the zone of injury and scarred bed

6. Faster recovery with its higher quality

7. Surgical procedure is more technically straightforward and can be performed with significant gain in operative time.

Compared to the musculo-tendinous transfer, there are also several advantages[16,39]:

1. Preservation of the original tendinous attachment

2. Preservation of the tension and orientation of the original muscle fiber

3. Minimal dissection of the target muscle and formation of adhesions

4. Possible reinnervation of several muscles

5. Possible simultaneous motor and sensory reinnervation

6. Simpler procedure with significant gain in operative time

7. Shorter time needed for immobilization

8. Obtained results rarely exceed grade M3, but the outcome is more predictable.

Factors favoring musculo-tendinous transfers are longer delays of surgery and absence of an active target muscle.

Functional priorities

The functional priorities for motor nerve transfers in patients with upper or total brachial plexus palsy are (1) strong and full range elbow flexion, (2) shoulder stabilization, (3) shoulder abduction and (4) shoulder external rotation. Lower priorities are elbow extension and preservation of brachio-thoracic pinch[28,31,41].

The recovery of all functions is equally important since this enables the movements, especially elbow flexion, to translate to functionality[41]. Elbow flexion could be restored by nerve transfers to the musculocutaneous nerve or its fascicles to the biceps and brachialis muscles. The musculocutaneous nerve contains from 3.069 to 7.911 myelinated fibers[42,43]. The average numbers in motor branches is 1.840 for the biceps and 1.826 for the brachialis muscles[44]. These muscles are responsible for elbow flexion and forearm supination.

Shoulder functions could be restored by nerve transfers to the axillary and/or suprascapular nerve, and the preferred option is a nerve transfer to both nerves. The axillary nerve contains between 4.967 and 8.437 myelinated fibers[42,43], with an average of 7.877, and 80% are motor fibers[45]. The number of motor fibers in the anterior branch of the axillary nerve ranges from 2.700 to 4.052[27,45]. The axillary nerve innervates the deltoid muscle, which acts as arm abductor. Its posterior part acts as an external arm rotator together with the teres minor muscle[19]. Finally, the suprascapular nerve contains approximately 3.500 myelinated fibers[42,43]. This nerve innervates the supraspinatus muscle that is responsible for initiation of arm abduction and the infraspinatus muscle responsible for arm external rotation.

Restoration of elbow extension is especially important in spinal cord injuries given the arm is especially important for support[33,34,35]. Nerve transfer could be performed using different donors to the long or medial branch of the radial nerve.

Donor nerves

Generally, there is no ideal motor donor nerve. Regardless, there are several important criteria for the choice of donor nerve[30,31,32]:

1. Expendable nerve or nerve with duplicated function

2. Close proximity to the recipient nerve, facilitating a direct anastomosis. This is the case in a large majority of infraclavicular intraplexal nerve transfers. On the contrary, nerve grafts are necessary in nerve transfers of the ipsilateral or contralateral C7 spinal nerve and in all extraplexal nerve transfers, except in spinal accessory to suprascapular nerve transfer.

3. Close proximity to the target muscle and its endplates to decrease the regeneration distance.

4. Pure motor fiber composition, possibly with a few sensory fibers

5. Large number of motor nerve fibers

6   Donor-recipient motor nerve fibers ratio 0,7 or greater promotes improved outcomes[44]. However, mismatch in the number of the motor nerve fibers should not always be a problem because only 20% to 30% of motor fibers are sufficient for reinnervation of muscles with a simple function, such as the biceps muscle. Moreover, collateral axonal sprouting may produce an excess of approximately 30% of axons.

7   Maximal nerve diameter matching enables more precise coaptation. The existing problem could be solved using several techniques such as epi-perineural anastomosis, fishmounting of the donor nerve epineurium, bundling of several donor nerve branches, and combined use of the donor nerves.

8   MRC grade at least M4 in donor innervation zone

9   Synergistic function with the recipient nerve offers more effective and faster cortical reintegration owing to efficient cerebral plasticity based on pre-existing cerebral and medullary interconnections[17,29,41].

The number of the myelinated nerve fibers in individual donor nerves vary widely:

1   Number of myelinated nerve fibers with mixed fiber composition averages 16.472 in C5, 27.421 in C6, and 23.781 in the C7 spinal nerve[43].

2   Anterior branches of the cervical plexus contains an average of 4.090 motor fibers.

3   The spinal accessory nerve contains an average of 1.700 motor fibers at its distal end.

4   3rd through 6th upper intercostal nerves contain between 1.200 and 1.700 myelinated fibers, with an average of 500 to 700 motor fibers at the midaxillary line. In the succeeding upper intercostal nerves, the number of fibers gradually diminshes for 10% at every 10 cm[46].

5   Thoracodorsal nerve contains 1.530 to 2.480 or up to 3.496 motor fibers, as well as approximately 1.453 in its lateral branch[46,47].

6   The medial pectoral nerve contains between 1.170 and 2.140 motor fibers, with an additional 400 to 600 in its branches[46].

7   The branch of the radial nerve to the long triceps head contains an average of 2.303 motor fibers, while the branch to the medial head includes 2.198 motor fibers[45].

8   The ulnar nerve branch to the flexor carpi ulnaris muscle contains an average of 1.318 motor fibers, while the median nerve branch to the flexor digitorum sperficialis muscle has 1.860[44].

Problems in the upper arm motor nerve transfers

There are several potential problems in nerve transfers for restoration of the upper arm motor functions, including (a) donor nerve morbidity, (b) possible co-contractions, (c) need for cortical re-education, (d) muscle loss for musculo-tendinous transfer, and (e) pre-existing donor nerve injury that may be a contraindication for nerve transfer.

Donor nerve morbidity is an important drawback, especially in cases with suboptimal grade M3 or M4 function of the synergistic muscles.

Potential functional loss after donor nerve section could be diminished in several ways depending on the type of nerve transfer:

1   In transfers of the ipsilateral or contralateral C7 spinal nerve, potential motor weakness and sensory loss recover spontaneously due to functional overlapping with neighboring spinal nerves[10, 39].

2   In spinal accessory nerve transfer, functional loss of the trapezius muscle could be diminshed using a distal section of the donor nerve with preservation of the upper and middle muscle parts, especially in cases with independent innervation from the C3 and C4 spinal nerves[5,6]. Paralysis of the serratus muscle and regained powerful external arm rotation may contribute to scapular winging[40].

3   In medial pectoral nerve transfer, important factors for diminishing functional loss of arm adduction are multiple innervation patterns of the nerve and preservation of some branches to the pectoral major muscle[18].

4   In thoracodorsal nerve transfer, some function could be retained using one of two branches to the latissimus dorsi muscle owing to a large number of motor fibers. Additiona;ly, partially preserved function of the synergistic teres major muscle in cases of predominant innervation from the C7 spinal nerve may be a contributig factor to arm adduction[21,47].

5   Preservation of one triceps branch (medial or lateral) of the radial nerve is sufficient for elbow extension[27,28].

6   In fascicular nerve transfers, significant motor deficit is exceptional[25,26].

Possible co-contractions could be useful in cases with synergistic function of the donor and recipient nerves, such as in spinal accessory nerve to the suprascapular nerve transfer. This also occurs in fascicular transfers with finger flexion when attempting elbow flexion or in medial pectoral nerve to musculocutaneous nerve transfer with arm adduction in the same situation[22,40]. Some authors favor this transfer in relation to the single or double fascicular transfers[40]. On the contrary, in spinal nerve transfers, there is a massive cross-innervation of the synergistic and antagonistic muscles with disabling co-contractions[14,29].

Function after nerve transfer is dependent on the donor nerve to some extent, and there is a need for cortical re-education. Some antagonistic functions, such as that of the deltoid muscle following the thoracodorsal or medial pectoral nerve transfer, could be successfully retrained in a relatively short period due to a closer functional relationship and cerebral cortical representation.

Muscle from the donor innervation zone is lost in musculo-tendinous transfer. Therefore, a balance of potential risks and benefits should be carefully estimated in individual cases.

A potential problem in nerve transfers is the degree of pre-existing donor nerve injury, which may result in variations in obtained results. There is always some damage to the nerves that are functional but located on the "edge" of lesion. Notably, muscle weakness becomes apparent when 50% of the motor fibers are lost. Fibrillation potentials detected on electromyography indicate potential injury to the donor nerve and may guide the selection of the type of nerve transfer[40].

Outcomes in the literature

Results of the most common nerve transfers in restoration of upper arm function were obtained from published systematic reviews / meta-analyses, demonstrating variable outcomes depending on the donor nerve choice for upper and total brachial plexus palsies. The comparisons below are nerve transfers versus nerve grafts.

Extraplexal nerve transfers included the spinal accessory and intercostal nerve transfers to the musculocutaneous and axillary or suprascapular nerves.

Generally, in transfers to the musculocutaneous nerve, grades M3 or more were obtained in an average 71% of cases (range: 64% to 88%) and grades M4 or M5 in an average 37% of cases[31,48]. Intercostal to musculocutaneous nerve transfer without nerve grafts resulted in grades M3 or greater in 72% of cases and in grades M4 or M5 in 41% of cases. In transfer with the use of nerve grafts, corresponding rates of recovery were 47% and 32%, respectively[48]. Spinal accessory nerve transfer to the musculocutaneous nerve resulted in grades M3 or more in an average 77% of cases[31,48,49]. Grades M4 or M5 were obtained in 29% of cases[48].

For nerve transfers in restoration of shoulder abduction, grades M3 or more were obtained in an average 73% of cases and grades M4 or M5 in an average 27%[48]. Spinal accessory to the suprascapular nerve transfer resulted in grades M3 or more in 79% to 95% of cases[49,50,51,52,53], with an average range for shoulder abduction of 50 degrees and for shoulder external rotation of 45 degrees[54]. Spinal accessory to the axillary nerve transfer yielded grade M3 or greater in 60% to 75% of cases[17,55]. Intercostal nerve transfer to this nerve resulted with grades M3 or higher in 33% to 67% of cases[17,48,55]. Available data for grades M4 or M5 in this transfer were limited.

Intraplexal nerve transfers included the medial pectoral nerve, thoracodorsal nerve, fascicles of the ulnar and median nerves, and triceps branches of the radial nerve, and demonstrated results superior to the extraplexal[51,54,56].

In restoration of elbow flexion, total rate of recovery, grades M3 or higher ranged between 96% and 98% of cases and grades M4 or M5 between 83% and 88% of cases[54]. Grades M3 or higher, and M4/ M5 for individual types of nerve transfer occurred in 100% and 91,6% of cases for the thoracodorsal nerve[19,21], 84% to 91% of cases and 64% for the medial pectoral nerve[18,19], 94% to 100% of cases and 70% to 100% of cases for Oberlin's single ulnar nerve fascicle[57,58,59,60], and 95% to 100% of cases and 80% to 95% of cases for single median nerve fascicle transfers, respectively[24,61].

In restoration of shoulder abduction, grades M3 or higher occurred in 86% to 93% of cases for thoracodorsal nerve[19,21,55], 81,8% of cases for the medial pectoral nerve[18,21], and 100% of cases for Somsak's triceps branch of the radial nerve transfers[27,62]. Grades M4 or M5 were present in 70,4%, 63,6% and 91,3% of cases, respectively. Average ranges of motion were 92 degrees (range: 65 to 120 degrees) for shoulder abduction and 93 degrees (range: 80 to 120 degrees) for shoulder external rotation[57].

Double fascicular transfer in restoration of elbow flexion yielded grades M3 or higher in 97% to 100% of cases and M4 or M5 in 85% to 100%[25,26,64]. However, some authors did not find any significant difference in outcomes for single fascicular transfers, except for the strength of elbow flexion[65,66]. Other studies have provided supportive evidence. Grades M3 or more were registered in 92,9% to 98,2% of cases for single and 95% to 100% of cases for double fascicular transfers. Corresponding rates of recovery grades M4 and M5 were 83% and 95% of cases with greater elbow flexion strength[60].

Dual nerve transfer for restoration of shoulder abduction and external rotation presents a simultaneous reinnervation of the suprascapular nerve using the spinal accessory nerve and the anterior division of the axillary nerve using one triceps branch of the radial nerve or intercostal nerves as donors[50]. M3 or greater grades of recovery for shoulder abduction were obtained in 100% of cases and grades M4 or M5 in 87% to 100% of cases with an average range of motion 122 degrees (range: 45 to 170 degrees). Corresponding rates of recovery for shoulder external rotation were 86% to 100% for grades M3 or higher and 87% for grades M4 and M5 with an average range of motion 108 degrees (range: 97 to 121 degrees), significantly higher than in single nerve transfers[58,60,63].

Comparative statistical analysis

Statististically significant differences in teh efficacy of nerve transfers for restoration of elbow flexion were documented between:

1. Double fascicular vs. single fascicular, thoracodorsal or medial pectoral nerve transfer in achieving M4 or M5[54,67]

2. Single fascicular, thoracodorsal or medial pectoral vs. spinal accessory or intercostal nerve transfer[17,68]

3. Intercostal nerve transfer without and with an interpositional nerve graft[48]

4. Intercostal nerve transfer without an interpositional graft vs. spinal accessory nerve transfer[48]

Statistically significant difference in nerve transfers for shoulder function, predominantly shoulder abduction was documented between:

1. Dual nerve transfer vs. single transfer to the axillary or suprascapular nerve[58,60]

2. Thoracodorsal or medial pectoral nerve transfer to axillary nerve vs. spinal accessory to suprascapular nerve transfer[54]

3. Spinal accessory to suprascapular nerve transfer vs. Transfer to the axillary nerve[48]

4. Spinal accessory vs. intercostal nerve transfer to the axillary nerve[48]

In the other situations, on the basis of recovery percentages, there was a trend toward superior results between intraplexal and extraplexal nerve transfers[17,54].

Generally, the available data demonstrated strong evidence in favor of double fascicular transfer in restoration of elbow flexion and dual nerve transfer in restoration of shoulder function[54,58,60,67].

Surgical strategies

Restoration of upper arm function – elbow flexion, shoulder abduction, and shoulder external rotation – is the main priority in nerve transfers for brachial plexus injuries, independent of the extent of injury.

In upper brachial plexus palsy, the result of motor nerve transfers may be complete functional recovery. In these cases, the surgical strategy is determined by integrity of the C7 spinal nerve given is importance in innervation of the thoracodorsal nerve and the motor branch to the long head of the triceps muscle.

In cases with avulsion of the C5 and C6 spinal nerve roots and an intact C7 spinal nerve, intraplexal nerve graft repair may be considered[31]. In recent reports, a combination of nerve transfers has been recommended, including dual nerve transfer for restoration of shoulder function and fascicular nerve transfers for restoration of elbow flexion[31,58]. Transfer of the medial pectoral and thoracodorsal nerves could be a valuable option for both functions[17,19,40]. The strategy in cases of the injuries with involvement of the C7 spinal nerve is similar. However, Somsak's procedure cannot be used in majority of cases and could be subsituted with transfers of the medial pectoral or intercostal nerves to the axillary nerve[69].

On the basis of our results, we favor transfer of the thoracodorsal and medial pectoral nerves in restoration of both functions. In restoration of shoulder function, we reinnervate only the axillary nerve. There are two reasons for this strategy: (a) supraspinatus muscle has important role in initiation of arm abduction and attracts the majority of axonal sprout in relation to the infraspinatus muscle, and (b) some external rotation may be established by reinnervation of the theres minor muscle and posterior part of the deltoid muscle, with contribution of long head of the biceps muscle[17,19].

In cases with total brachial plexus palsy, extraplexal nerve transfers are the only possibility. Our proposed combination includes spinal accessory to the suprascapular and upper intercostals to the axillary and musculocutaneous nerves. Another possible option is the contralateral C7 spinal nerve transfer to the lateral and posterior cords[69].

Restoration of elbow extension in C5 to C7 or total brachial plexus palsy is less critical but should be considered whenever possible, as it provides better elbow control via antagonistic feedback to the elbow flexors[63]. Transfers to the radial nerve or its branches to the triceps muscle have been attempted using different donors depending on the extent of injury[70].

Conclusions

On the basis of this review and the results in the literature, we make several conclusions with practical implications.

1   Patient selection is crucial, especially in terms of age, time elapsed from injury, and readiness of the patient to wait 6 to 9 months for reinnervation in contrast to the 4 and 8 weeks needed for activation following musculo-tendinous transfer.

2   Primary exploration of the brachial plexus is still advisable in a large number of cases because evaluation of the extent of brachial plexus injury and identification of viable proximal nerve stumps can inform the operative approach. Exceptions are the presence of scarred bed or associated major vascular injury.

3   Nerve transfer should be performed preferably between 3 and 5 months.

4   Reinnervation of the recipient nerve should be done as close as possible to the target muscle in order to reduce reinnervation time.

Therefore, neurotization of the recipient nerve at its periphery is more effective than in at its central part. Additionally, it is crucial to ensure an adequate length of nerve stumps for tensionless direct anastomosis.

5   Synergistic muscle function between the donor and recipient nerves requires less postoperative re-education based on pre-existing cerebral cortical and medullary interconnections.

6   Results of ipsilateral nerve transfers are superior to these of contralateral ones.

7   Results of intraplexal transfers are significantly better than extraplexal transfers.

8   Double fascicular transfer for recovery of elbow flexion offers better quality of recovery compared to single nerve transfers.

9   Dual nerve transfer for restoration of shoulder function is more effective method than single nerve transfers. Recovery rates for shoulder external rotation are lower than for shoulder abduction.

10   Nerve transfers using single spinal accessory nerve transfer have not proven to be superior because of importance of the scapular motion associated with this nerve. This nerve should not be considered as particularly expendable.

11   Intraplexal nerve transfers performed earlier than 6 months following injury in patients under 40 years of age offer excellent results.

Disclosures

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