Chapter

Risk and Reward: Avoiding Donor Morbidity and Maximizing Results in Nerve Transfer Surgery

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Abstract

Nerve transfers have revolutionized outcomes in brachial plexus and peripheral nerve surgery. The ability to plan and execute effective and safe nerve transfers is now integral to providing contemporary reconstructive nerve surgery. This chapter provides an academic and philosophical approach to patient care. It includes details of preoperative planning and intraoperative techniques in sufficient practical detail to help surgeons both minimize risk and maximize results. This includes thorough discussion of techniques for interfasicular dissection, management of nerve branching, intraoperative nerve mapping, optimizing purity and quality of selected donor nerves and decision-making about donor neurotomy and preferred level of secondary nerve coaptation. These concepts and techniques provide the opportunity to improve results in known and familiar nerve transfers, as well as provide the opportunity to undertake new procedures with the best chance of success and the lowest risk of harm.

Keywords: nerve transfer, nerve injury, brachial plexus, peripheral nerve

1. Background

Nerve transfer surgery has revolutionized outcomes in both peripheral nerve and brachial plexus injuries. Despite first being described many decades ago, nerve transfers have not been widely adopted until recently [1, 2]. In essence, nerve transfers are attempts to repurpose existing functions toward more important, yet deficient functions. They require a full understanding of the deficit, and an ability to balance reconstructive needs with any potential donor sacrifice. This chapter aims to discuss donor morbidity in detail, which in almost all nerve surgery can be completely avoided with meticulous planning and technical care. By harvesting maximal donor nerve while avoiding donor morbidity, results with nerve transfer surgery can be safely optimized. It is incumbent upon all nerve surgeons to offer their patients the best possible result and the appropriate and sophisticated adoption and execution of nerve transfers will certainly contribute greatly to this cause.

2. An academic and philosophical approach to nerve transfer

The virtues of nerve transfer techniques are multiple. It is well accepted that one feature of nerve transfer surgery which portends an improved prognosis compared to grafting is that of the single neural coaptation [3]. Each neural coaptation has an obligate axonal dropout and therefore the fewer the coaptations the greater the number of axons which arrive at the end target irrespective of the original donor axon supply. It is additionally well known that by peripheral nerve transfers the surgeon is able to select deliberately either a pure or near pure motor or sensory axon pool for a motor or sensory reconstruction respectively. In the case of lower motor neuron injury, the surgeon is able to confirm the integrity of motor donor peripheral axons prior to using them for the reconstruction. A further advantage of nerve transfers when undertaken in the periphery for a peripheral target reconstruction is the short regeneration distance required [4]. There are many advantages of a short regeneration distance which all relate to time. The shorter the regeneration distance the earlier that the target receives its axonal input and therefore the less target organ attrition. In the case of motor reconstruction this means less motor endplate drop out. This enhances the number of motor fibers which can be recruited in the muscle and thereby enhances the amount of power which can be generated by the reanimated muscle. The shorter time between surgery and target reinnervation also means that surgery is still a reasonable proposition even if a patient has been referred late or has a delay to surgery for whatever reason. This therefore means that a greater pool of people can be assisted by virtue of this type of surgery compared to more traditional techniques.

Less discussed in the literature is the fact that many traditional reconstructions rely on a mixed motor and sensory donor nerve being utilized via a graft requiring two coaptations, in order to reconstruct a mixed motor and sensory recipient. This has a potentially profoundly negative impact of likelihood of reconstructive success. For illustration, if one accepts that each coaptation is associated with an approximate 50% axonal dropout then significant attrition occurs between the proximal donor and its distal targets. Assuming a 100% axon count in the reconstructive donor nerve the most axons that can arrive at the target is 25% having crossed two coaptations. If however one additionally considers a mixed 50% motor and 50% sensory donor is being used to reconstruct a mixed motor sensory recipient then this final target axon count is in fact 12.5%.

It is important to understand the reality that many traditional nerve grafting techniques are inherently unpredictable and imprecise reconstructive technique. The surgeon is then free to analyze individual clinical problems and attempt reconstructions based on techniques which both scientifically and experientially have a greater chance of success (**Table 1**).

	Nerve graft	Nerve transfer
Distance to target	Often long	Generally short
Number of coaptations	2	1
Donor axons	Often mixed motor/sensory	Usually specific
Quality of donor axons	Variable	Usually excellent by design
Early reinnervation	Sometimes	Usually
Suitable for late surgery	Uncommonly	Often
Operative scars and dissection	Long/multiple	Generally short and few

Table 1.
Comparison of nerve grafts and nerve transfers for reinnervation.

3. Intraoperative techniques

3.1 In transfers requiring intraneural neurolyses

The topography within peripheral nerves is extensively examined and discussed in the literature. It is often stated that this topography is critical to nerve transfer surgery in terms of selecting donor fascicles. While it is true that an understanding of this internal neural topography can expedite surgery and shorten operative times, reliance on internal topography at the expense of extensive intraneural dissection is in fact a risk for donor morbidity in nerve transfer surgery. The topography within an individual peripheral nerve although commonly similar between individuals is not uniform and as such the best way to minimize the risk of a donor deficit after harvesting a nerve for a nerve transfer, is an exhaustive and meticulous intraneural neurolysis and selective micro stimulation of individual fascicles and sub fascicles prior to a neurotomy.

In a transfer such as an ulnar fascicle to a nerve to biceps [5], it is this author's preferred technique to dissect the recipient nerve first. Once the likely site of nerve repair is known and allowing for the length that will be lost in transferring the donor fascicle to the recipient nerve, the site for exploration of the donor nerve is chosen. This sequence avoids unnecessarily dissecting donor nerves over a longer length than required, thereby reducing both operative time and inadvertent donor morbidity. At the chosen site and over a length of approximately 20 mm the ulnar nerve is dissected under the operating microscope by gently and bluntly teasing apart of individual fascicles. No division of axons is required to undertake this process. Each individual fascicle is looped with a small piece of background or colored vessel loop. Each piece of surgical background/vessel loop is clipped with a small or large crushing Weck clip which does not touch the nerve itself. These clips can be applied in a single, double, triple or quadruple fashion in order to label fascicles. In this way, it is easy to separately identify eight or more fascicles within a donor nerve (see **Figure 1**).

A chart can be constructed with these individual fascicles on the Y-axis and the observed function of these fascicles utilizing micro nerve stimulation on the X-axis. By separating these fascicles and insulating them from the other fascicles using dry microsurgical strolls, it is possible to see the distal function in the forearm or hand of each individual fascicle and document this in the chart (see **Figure 2**).

It is the author's preference to in fact undertake this stimulation at least twice for each fascicle, preferably separated by a time interval. Usually all fascicles are stimulated in turn and the chart is constructed. The chart is then observed to determine

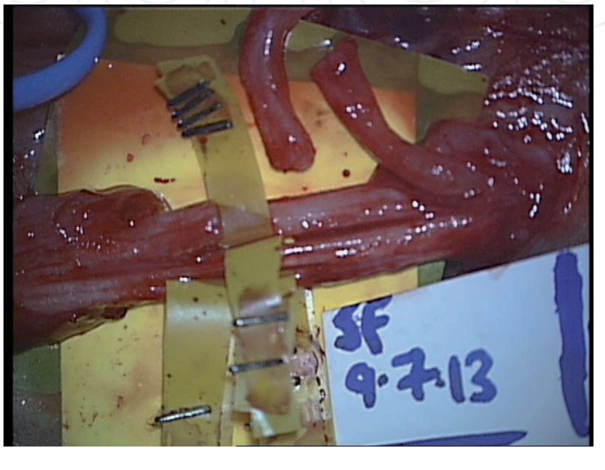

Figure 1.
Dissected and labeled ulnar nerve fascicles after neurotomy for secondary nerve repair to biceps nerve.

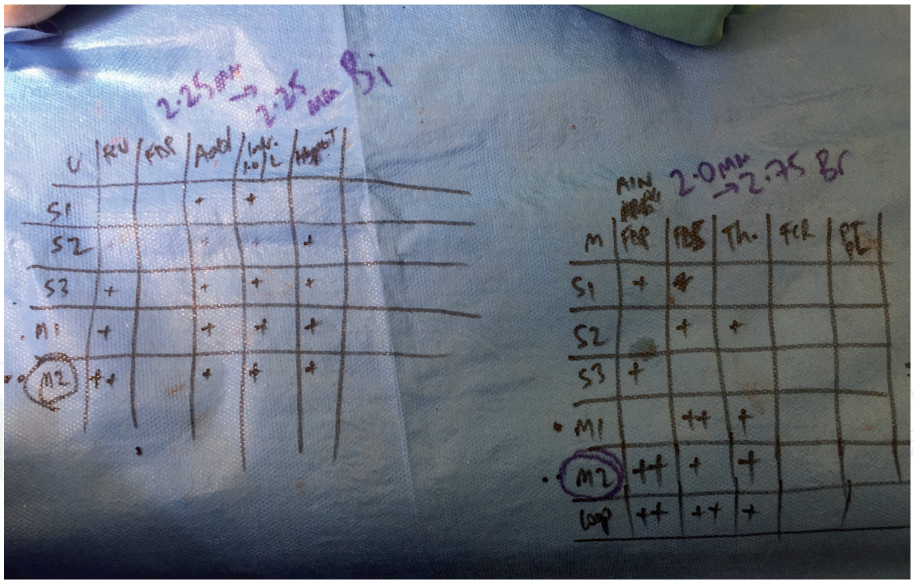

Figure 2.
Fascicular mapping chart. Note: "Y axis" with different fascicles listed and labeled, and "X axis" with intraoperative stimulation findings of those fascicles, and ultimate donors chosen circled and size matches listed on top to biceps (Bi) and brachialis (Br).

which fascicle or fascicles are most appropriate to be sacrificed for the nerve transfer. After this provisional decision has been made all fascicles are again stimulated. This is to ensure that the observed peripheral function remains the same and that no significant errors in stimulation, insulation, observation or recording have been made.

Given that the proposed donor nerve has now been observed to be functioning and its condition already evaluated without division under the operating microscope, the next step is to divide the recipient nerve. This division is undertaken as close to the biceps muscle as is possible to allow a tension free high quality nerve coaptation. Only now that the recipient nerve is observed to be in good condition for receipt of the nerve transfer at this level is the donor nerve sacrificed for use. The neurotomised fascicle(s) are then transferred and secondary nerve coaptation to the biceps nerve is undertaken under the operating microscope.

The technique described here for the ulnar to biceps nerve transfer can be utilized for any nerve transfer where the donor fascicle or nerve being used is less than the whole of the donor nerve being dissected. Other examples in common use are the partial median to brachialis and the partial contralateral C7 use for complete brachial plexus palsy. The same steps in the same order will maximize the surgeon's ability to provide maximal axonal input to the reconstruction while minimizing the risk of donor morbidity.

3.2 For nerve transfers not requiring intraneural neurolysis

In nerve transfers where no intraneural neurolysis is required to determine which axons will be used for the reconstruction, several of the previously discussed principles still apply. A good example of this is the triceps nerve(s) to the axillary nerve transfer [6]. It is usual for there to be approximately eight or so motor nerves to the triceps in the author's experience. It is important prior to deciding which nerve or nerves will be used in the reconstruction to determine each intact nerve to triceps' contribution to that triceps' function. Specifically the surgeon should observe each nerves diameter, length and the strength of contraction it elicits in the triceps when stimulated. The authors preferred stimulation is using a disposable nerve stimulator on its lowest setting of 0.5 mA. In this nerve transfer example one is therefore able sacrifice sufficient branches to triceps to maximize the axonal input

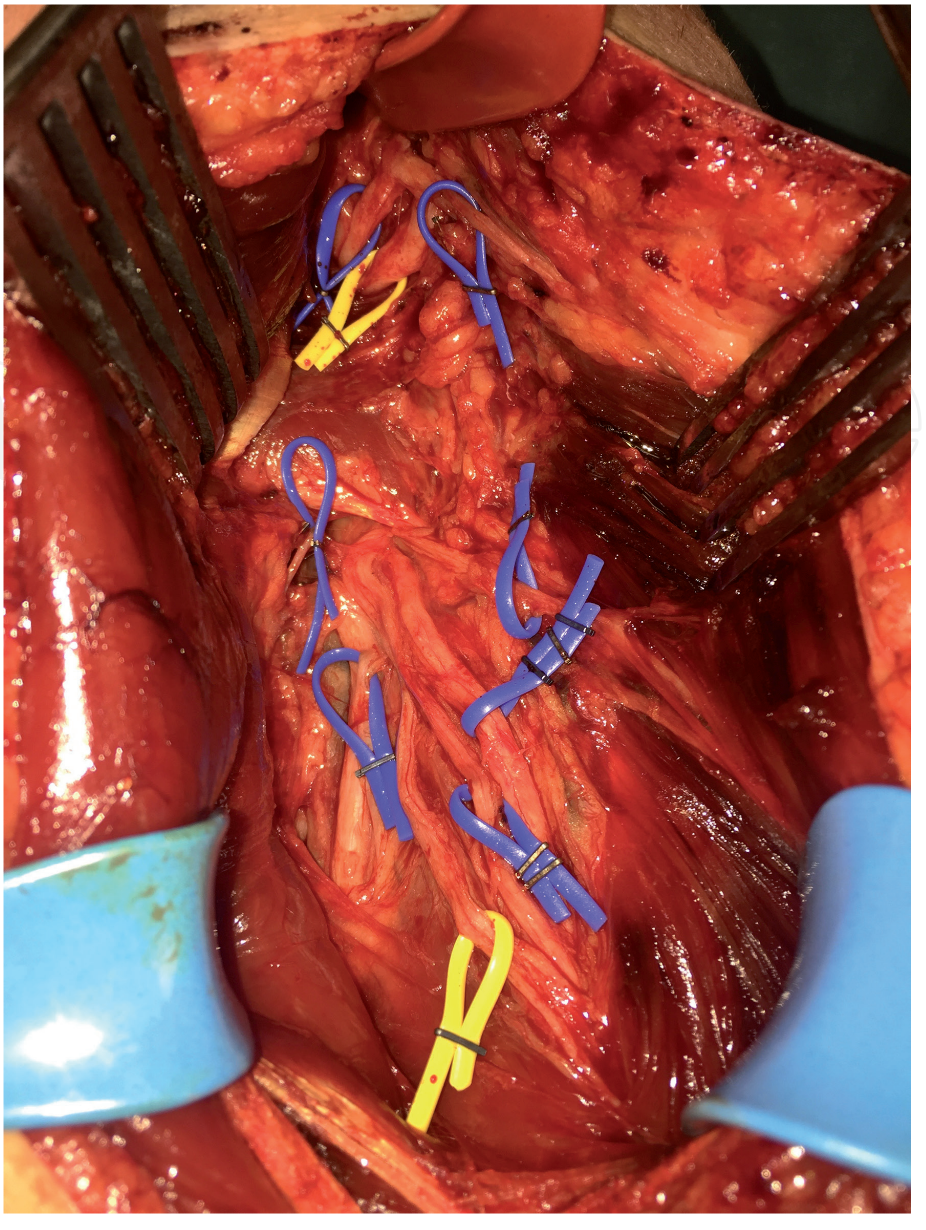

Figure 3.
Dissected and labeled triceps to axillary nerves. Note: Planned recipient anterior axillary nerve and donor triceps nerves looped in yellow ready for use; sensory posterior axillary nerve, dissected other triceps nerves plus radial nerve proper all looped in blue.

to the axillary nerve being reconstructed while maintaining sufficient function in the residual triceps. It would be an error to take a single branch triceps in a patient where multiple branches could safely be harvested because the axonal input for the reconstruction would therefore be less. Similarly it would be an error in these patients to take multiple branches of triceps without ensuring that there were multiple residual branches to maintain triceps function. Both of these potential errors can only be avoided by an exhaustive search for all nerves entering triceps and selectively isolating each and stimulating it to determine its function (**Figure 3**).

4. Decision-making about donor dissection, neurotomy level and branch management

Throughout the dissection of potential donor nerves, especially long nerves with multiple branches, it is important to be aware of the implications of the management of nerve branches, as well as the ultimate level for the donor neurotomy.

As one dissects any potential donor nerve, the more distal the ultimate neurotomy, the greater the preservation of proximal function can be, but the lower the axon count being used for the reconstruction. Also with a distal neurotomy and therefore long donor nerve, the nerve coaptation is closer to the target and benefits from a short regeneration distance as well as being more likely to be below the level of the nerve lesion. Alternatively, the more proximal the ultimate donor neurotomy, the greater the axon count being used for the reconstruction, but the greater the donor morbidity as well as increasing the regeneration distance and the risk of not being below the level of nerve injury (**Figure 4**).

An excellent example of this is when dissecting the mid and distal accessory nerve, commonly used for reanimation of the suprascapular nerve. In this situation the surgical goal is restoration of shoulder function, by reanimation of the supraspinatus and infraspinatus muscles. It is important to remember however, that the trapezius muscle also contributes to shoulder function. As such, there is a delicate balance between preserving maximal function in the upper trapezius muscle, while sacrificing and utilizing sufficient axons from lower trapezius (distal accessory nerve) for the reconstruction.

Performing the distal spinal accessory to suprascapular nerve transfer from a posterior approach facilitates management of the above issues. While the posterior approach requires lateral positioning of the patient and a more difficult dissection compared to an anterior approach, with care it allows full delineation of the donor and recipient anatomy before committing to any neurotomies. Once the recipient nerve has been dissected and evaluated, a decision can be made regarding what level on the SSN proper, or even the supraspinatus and infraspinatus nerves individually, the coaptation is planned. This level can be compared with the position, length, caliber, branching and potential pivot point of the mid-distal accessory nerve. It is desirable whenever possible, to preserve those branches into upper and middle trapezius which are too short to be used in the reconstruction, such that this component of trapezius is not denervated without any reconstructive benefit. Sometimes once all the exploratory surgical findings are known, if the suprascapular nerve approaching the notch is in excellent condition, then a decision can be made to use a slightly longer recipient nerve and a slightly shorter donor nerve

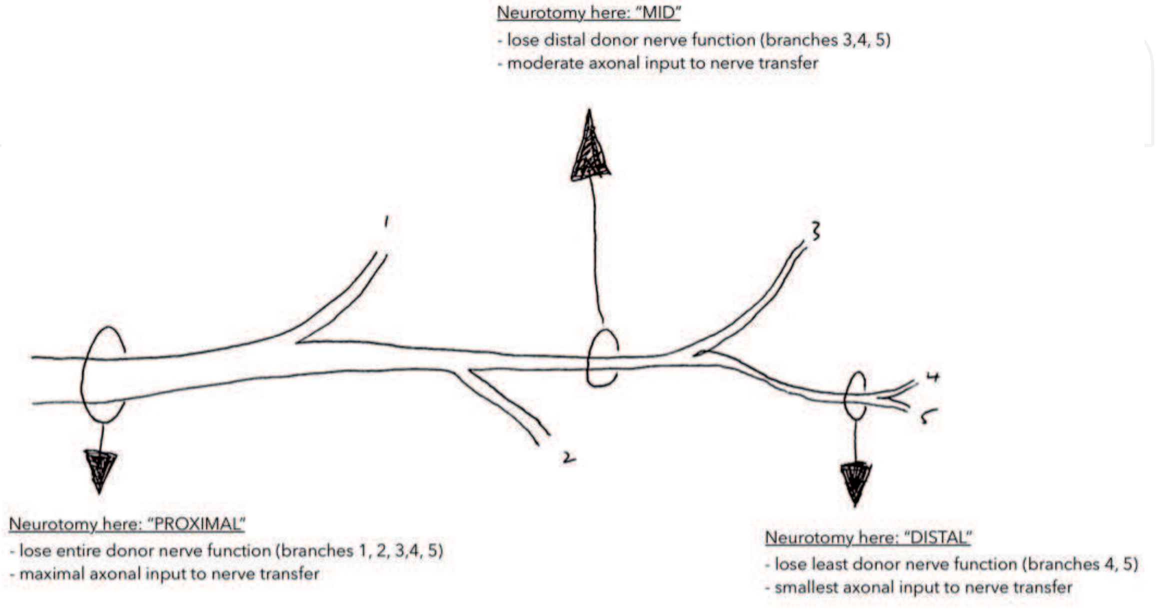

Figure 4.
Schematic representation of levels of donor neurotomy.

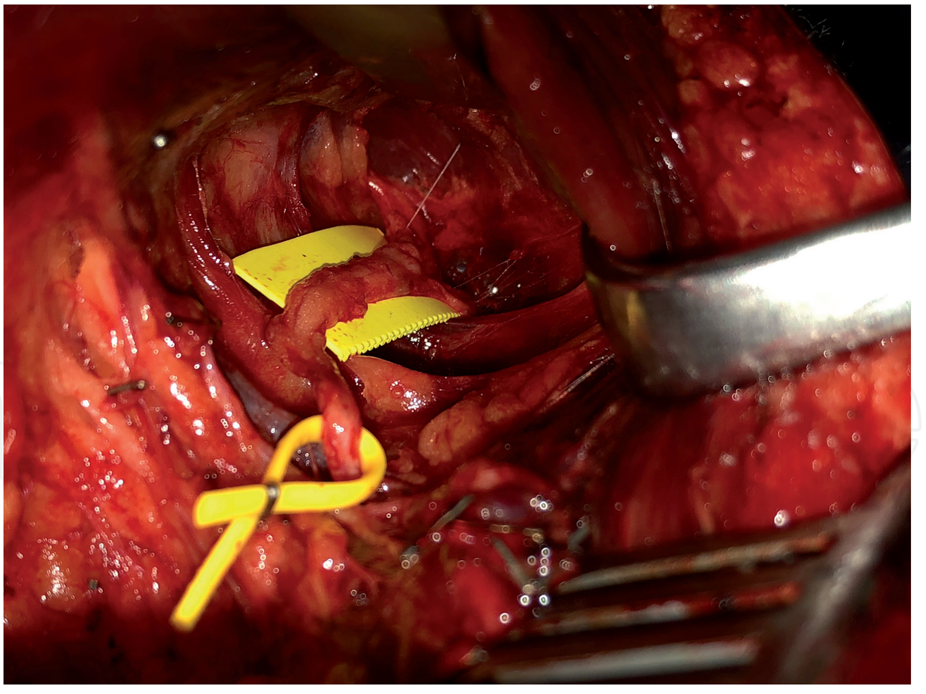

Figure 5.
Distal accessory nerve donor dissected. Note: Long length of donor dissected without needing to divide branches, and terminal branches diverging distally.

Figure 6.
Completed nerve repairs terminal accessory to both supraspinatus and infraspinatus nerves. Note: Posterior approach has allowed very distal repairs, close to target with good size matching, immediately distal to level of divided suprascapular ligament.

or lower pivot point in order to preserve the proximal and mid trapezius muscle branches. Only if such a trapezius branch still impedes tension free nerve transfer should it be sacrificed to prevent possible avulsion of the ultimate nerve repair (**Figures 5** and **6**).

5. Optimizing purity and quality of donor nerves

It is important in all motor nerve transfers to keep motor donors as purely motor as possible in order to maximize target outcome as well as minimize sensory donor morbidity. When dissecting motor donor nerves for use, it is critical that where possible any sensory components or branches are identified such that they are not

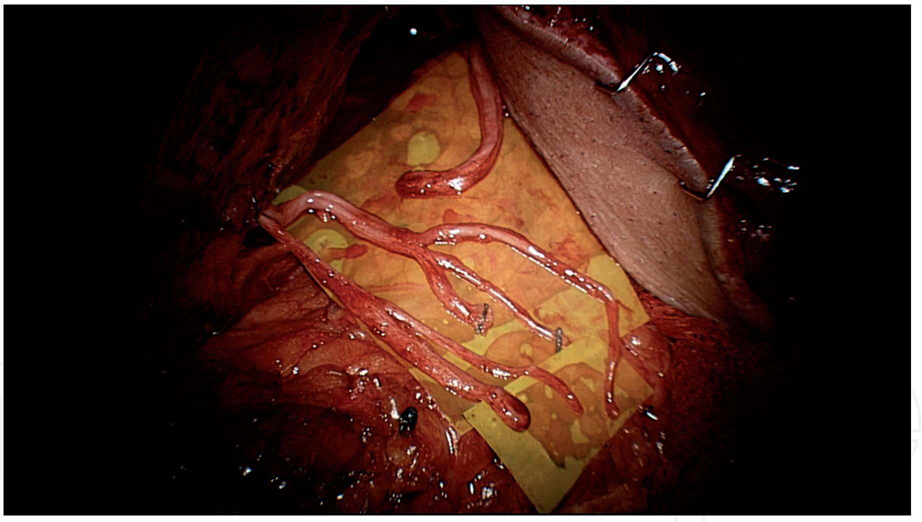

Figure 7.
Dissected and labeled intercostal nerves for gracilis flap. Note: Known sensory components of intercostal nerves labeled by small clips, with motor branches left unclipped ready to use to innervate free gracilis muscle flap, uppermost in picture.

inadvertently included in the nerve coaptation. Depending on the nature of the nerve transfer, techniques for this differ.

For fascicular nerve transfers, the insulated stimulation and selective fascicular mapping described above contributes greatly to this process. For triceps nerve donors the individual anatomical exploration and labeling of separate nerves achieves the same outcome of knowing which nerves are motor and adequately powered. One should always remember however that a fascicle or nerve which does not stimulate can either be a sensory fascicle, a temporarily neuropraxed fascicle, or a fascicle which has either a proximal or a distal permanent injury.

Intercostal nerve dissection is different due to the large sensory nerves which branch at intervals from what are mixed motor/sensory parent nerves. In these dissections, as one dissects along the intercostal nerve and finds what are clearly sensory branches, it is wise to use a small surgical clip applied to the end of these sensory nerves before they are divided, such that at a later stage they are clearly identifiable and used only for sensory targets. In this way the proportion of total axons which are actually motor axons ultimately used for motor reconstruction can be maximized.

The same techniques apply in reverse when dissecting sensory nerve donors, in order to not inadvertently include motor fibers in the reconstruction (**Figure 7**).

6. Patient selection

The techniques described here are very effective in restoring function when used in appropriate patients. Accurately determining which patients require which operations at what time point is the first step toward success.

Patients must have a stable skeleton with supple joints. They must also be available, motivated and cognitively capable of undergoing their postoperative rehabilitation.

The timing of surgery is critical. For a known open nerve lesion, reconstruction is best undertaken as soon as there is an appropriately skilled team and resourced operating theater. By contrast, the common closed avulsion lesions generally require greater investigation and preoperative assessment to determine whether surgery is necessary, or whether spontaneous recovery is likely. In this way, unnecessary surgery on spontaneously reversible neuropraxic lesions can be avoided.

In all acute or subacute patients, once it is clear that nerve reconstruction will be required, surgery should be scheduled as soon as possible such that the denervation time of native muscles requiring reinnervation is minimized.

In patients referred very late, there can paradoxically be less urgency. This is because in these patients there is no meaningful chance of reinnervating their native muscles. In these patients, active function is achieved by either pedicled transfer of intact regional muscle/tendon units, or by importing a free functioning muscle flap. In both pedicled or free muscle transfer it is possible to take the time to optimize the passive range of motion of all joints, as well as undertake preeducation and training of the patient before their definitive surgery because the urgency of reinnervating their original muscles is not present in such cases. In the case of pedicled muscle/tendon transfer there is no denervation time because no neurotomy and nerve repair is required. In the case of a free functioning muscle flap, the denervation time begins at the time of reconstruction, rather than at the time of initial injury, as the transferred free muscle flap is neurotized by using nerve transfer.

7. Example cases

7.1 Case 1: complete musculocutaneous nerve palsy as part of C56 palsy

A 32-year-old man sustained complete left C56 root avulsions in a motorbike accident. Four months later he underwent multiple reconstructions by nerve transfer, including median to brachialis and ulnar to biceps nerve transfers. By 15 months postoperatively, he could flex his elbow with at least 12 kg dumbbell in his hand (**Figure 8**).

7.2 Case 2: failed axillary nerve grafting—salvage with triceps nerve transfer

A 17-year-old footballer while undergoing a right shoulder stabilization procedure sustained an iatrogenic combined nerve and arterial injury. He had immediate

Figure 8.
Postoperative result of nerve transfers to biceps and brachialis. Note: Excellent restoration of muscle bulk and range of elbow flexion.

Figure 9.
Postoperative result of salvage nerve transfer using triceps donors to right axillary nerve. Note: Full abduction of shoulder, with excellent bulk of deltoid.

vascular repair, and axillary nerve grafting on day four after injury. When at 8 months after grafting there was no evidence of nerve regeneration or muscle reinnervation, he was taken back for exploration and underwent a salvage nerve transfer using two separate triceps nerves to reanimate the extreme distal end of the anterior branch of his axillary nerve (**Figure 9**).

7.3 Case 3: complete brachial plexus palsy-free muscle flap with accessory nerve transfer

A 39-year-old man was referred with a complete right brachial plexus palsy after a motorbike accident into a tree. He underwent multiple reconstructions, including a free functioning gracilis muscle flap, innervated by the spinal accessory nerve transfer, which was undertaken 5 months after his injury. This muscle was inset proximally on the clavicle and tunneled distally in the arm, under a PT/FCR pulley at the elbow, to all four FDP tendons, thereby acting as both and elbow flexor and a finger flexor (**Figure 10**).

Figure 10.
Postoperative result of free functioning gracilis muscle, innervated by accessory nerve transfer. Note: Bulk of reinnervated gracilis muscle superiorly and excellent active range of elbow flexion restored.

8. Conclusions

Nerve transfers have completely transformed the expected surgical outcomes for many nerve deficits and patterns of nerve injury. The way in which nerve transfers are used depends on individual patterns of and time since injury. The best possible outcomes depend on careful balancing of the risks and rewards in each individual patient. Informed, realistic and strategic preoperative planning, combined with meticulous intraoperative dissection, diligent appraisal of intraoperative findings and considered intraoperative decision-making prior to final execution of technically optimized nerve transfers allows the minimization of donor morbidity and maximization of surgical outcome.

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