Nerve Transfer Techniques in Injuries from the Upper Limb

Técnicas de transferencia nerviosa en lesiones del miembro superior

Francisco Martínez Martínez[1] B. Ñíguez Sevilla[2] J. García García[2] A. García López[3]

[1] FEA (field medcial expert), Orthopaedics and Traumatology Surgery, Hospital Clínico Universitario Virgen de la Arrixaca. Murcia, Spain
[2] Resident, Orthopaedics and Traumatology Surgery, Hospital Clínico Universitario Virgen de la Arrixaca, Murcia, Spain
[3] FEA (field medcial expert), Orthopaedics and Traumatology Surgery, Hospital General de Alicante, Alicante, Spain

Address for correspondence Francisco Martínez Martínez, C/ Canovas del Castillo n°7- 4°a. 30003-Murcia, Spain (e-mail: fmtnez@gmail.com).

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Abstract

Proximal nerve injuries from the upper limb or the braquial plexus are associated with a poor prognosis, even with prompt repair. In the last few decades an increase in nerve transfer techniques has occurred, by which a denervated peripheral nerve is reinnervated by a healthy donor nerve. Nerve transfers are indicated in proximal brachial plexus injuries where grafting is not possible or in proximal injuries of peripheral nerves with long reinnervation distances.

Nerve transfers represent a revolution in peripheral nerve surgery and offer the potential for superior functional recovery in severe nerve injuries. In complete brachial plexus injuries, there are being studied the existence of nerve roots (intraplexual transfers). If they do not exist, the transference of nerves out of the plexus are used (extraplexual transfers) as the spinal accessory nerve, the phrenic nerve, the intercostal nerves, etc.

In this update paper, the different motor intra and extraplexual nerve transfer techniques are going to be reviewed.

Keywords
- nerve transfers
- brachial plexus
- nerve injury

Resumen

Las lesiones nerviosas proximales tanto de miembro superior como del plexo están asociadas con un mal pronóstico, incluso con una reparación temprana. En las últimas décadas ha existido un aumento de técnicas de transferencia nerviosa, mediante las cuales un nervio periférico denervado es reinervado por un nervio donante sano. Las transferencias nerviosas están indicadas en lesiones del plexo braquial proximal donde no es posible el injerto o en lesiones proximales de los nervios periféricos con largas distancias de reinervación.

Las transferencias de nervios representan una revolución en la cirugía del nervio periférico y ofrecen el potencial para la recuperación funcional superior en lesiones nerviosas graves. En las lesiones completas del plexo braquial se investiga la existencia

Palabras Clave
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- plexo braquial
- lesión nerviosa

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de raíces disponibles para utilizarlas como donantes de axones (transferencias intraplexuales). En caso de no existir, se recurre a las transferencias de nervios que no forman parte del plexo (transferencias extraplexuales) como pueden ser el nervio espinal accesorio, el nervio frénico, los nervios intercostales, etc.
En el presente artículo de actualización, se hará una revisión de las técnicas quirúrgicas de transferencias nerviosas motoras tanto intra como extraplexuales.

Introducción

In the 1970s and 1980s, there was great enthusiasm for reconstructive brachial plexus surgery thanks to the advent of ground-breaking techniques, although this enthusiasm declined due to the stagnation of results obtained.

We define nerve transfer or "neurotization" as a surgical technique consisting of sectioning a nerve or fascicle thereof, which we shall call the donor, sacrificing its original function, to connect it with the distal stump of a recipient nerve or fascicle, whose function was lost during the trauma. With this technique, the loss of donor nerve function is unavoidable, so it is necessary to assess the risk-benefit ratio of this loss.

Initially, this type of technique was indicated when it was impossible to perform neurorrhaphy, with or without grafting, of the injured nerve. This type of situation occurs in the brachial plexus when a cervical root is avulsed from its origin at the level of the spinal cord. However, and given the good results obtained with this technique, nerve transfers have been used in some cases in which the roots of the plexus were preserved.

In complete lesions of the brachial plexus, we will study the existence or otherwise of available roots to be used as axon donors (intraplexal transfers). If they do not exist, we will resort to the transfer of nerves which are not part of the plexus (extraplexal transfers) such as the spinal accessory nerve, the phrenic nerve, intercostal nerves, etc. In the event of the avulsion of all roots, extraplexal transfers are the only methods of reinnervation available.

The success rate of neurotizations increases if the fascicles of the donor nerve coincide with those of the recipient in axonal number, size and function as agonistically as possible, while performing the neurorrhaphy as close as possible to the target muscle is also a good prognostic factor.

In this article, we will review the surgical techniques available in the therapeutic arsenal of this pathology.

Intraplexal Neurotizations

Radial Nerve

The radial nerve is most the commonly affected one in upper limb injuries. Radial palsy can result from a variety of causes such as direct trauma, especially in humeral shaft fractures, compressions, tumours, local inflammation, idiopathic neuritis or iatrogenic injury during surgery. It can be affected proximally, by a brachial plexus injury, or even distally in a posterior interosseous nerve lesion.

The treatment of these lesions will depend on the cause of the paralysis, the duration of the symptoms, and the level or extent of the neurological deficit. When not associated with open lesions, an expectant attitude is maintained for several months before surgery. When a laceration or wound is present, an immediate surgical examination is often required.

Anatomy

The posterior cord of the brachial plexus gives rise to the radial nerve, with the contribution of the roots C5-T1. The radial nerve lowers around the humeral shaft through the spiral canal, after which it passes below the lateral triceps belly, on the surface of the lateral intermuscular septum. It innervates the brachioradialis and the *extensor carpi radialis longus* before crossing the elbow and splitting into the posterior interosseous nerve (PIN) and the superficial radial nerve.

The superficial branch of the radial nerve goes below the brachioradialis to innervate the radial region of the dorsum of the wrist and the hand.

The PIN surrounds the radial head below the supinator muscle and above the interosseous membrane. It innervates the *extensor carpi radialis brevis*, the supinator, the *Extensor Digitorum Communis*, the *Extensor Digiti Minimi*, the *Extensor Carpi Ulnaris*, the *Abductor Pollicis Longus*, and the *Extensor Pollicis Longus, Extensor Pollicis Brevis* and the *Extensor Indicis Proprius*. The origin of the innervation of the *extensor carpi radialis brevis* is highly variable, with the possibility of it appearing proximally to the formation of the PIN or beside the sensory branch.

Therefore, radial nerve injury will produce a deficit in the extension of the fingers and thumb, with a limited radial extension of the wrist, in addition to the sensory involvement.

Transfer of the Musculocutaneous Nerve to the Radial Nerve

This technique was described in 1947 by Lurje[1], and was designed for repair of defects greater than 6 cm. During the procedure, the musculocutaneous nerve must be located in the interstitial space located between the biceps muscle and the anterior brachialis muscle once it has already given the branches to the coracobrachialis muscle, when branching out to innervate the biceps, usually with 2 or 3 branches. In the middle third of the arm, the nerve will more or less consistently give a branch to the anterior brachialis muscle, while in the distal third it sometimes provides 1 or 2 more branches for the same muscle. In the flexure of the elbow, lateral to the bicipital tendon, the musculocutaneous nerve occasionally gives a last branch for the brachialis muscle, later transforming into the lateral antebrachial cutaneous nerve.

The musculocutaneous nerve is sectioned in the area immediately distal to the origin of the main branches for the biceps muscle, and proximal to the distal branches of the brachialis muscle, so flexion of the elbow is not significantly

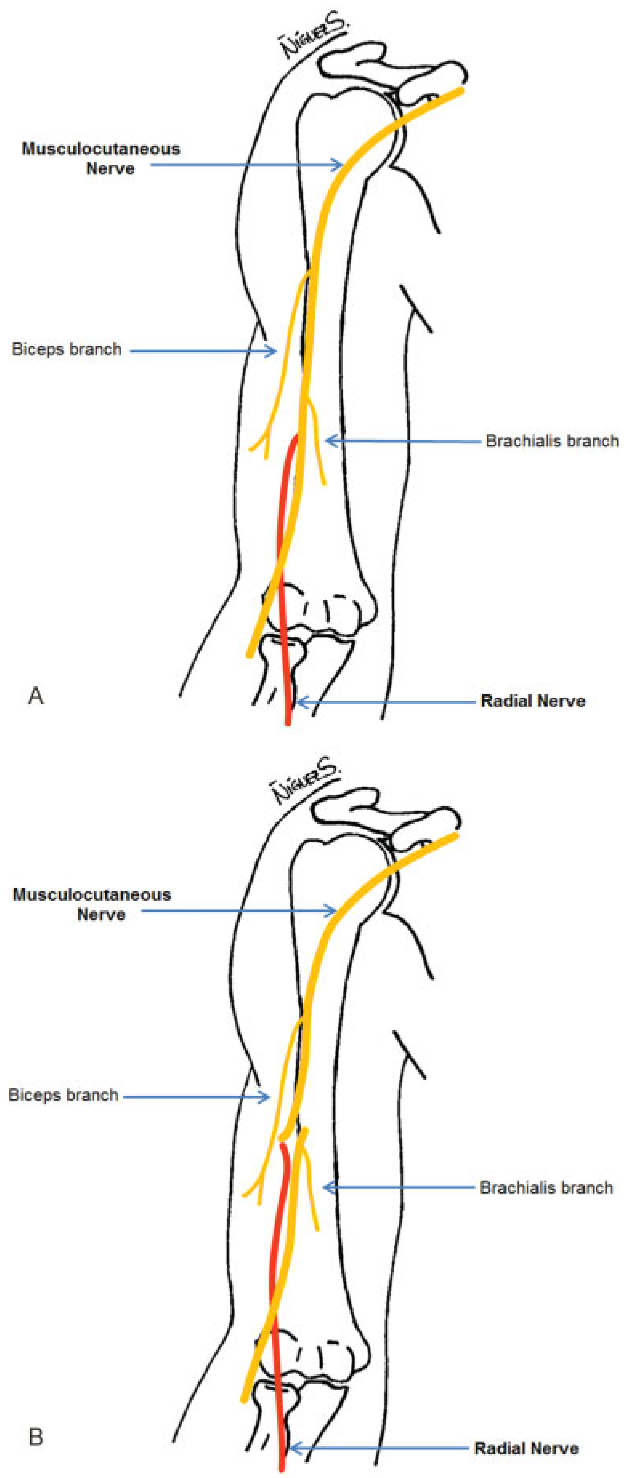

Fig. 1 A. Anatomy of radial nerve and musculocutaneous nerve. B. Transfer of musculocutaneous nerve, distal to branch innervating biceps brachii, to radial nerve.

affected. The biceps, whose innervation remains intact, will compensate for the function lost by the denervation of part of the brachial. Therefore, this author considers that the musculocutaneous nerve, after being sectioned in the indicated place, may be used to neurotise the radial nerve by means of terminus-terminal suturing in major defects located in the upper two thirds of the arm or in the axilla. (►**Fig. 1**)

To carry out this surgery, it is essential that the proximal end of the radial nerve section is located proximally at more than 6-7 cm from the lateral condyle of the humerus, in order to perform the suturing without tension.

This type of surgery is especially useful when there is a major defect in the radial nerve accompanied by median and ulnar nerve injury. In these cases, tendon transfers are not useful.

Transfer of Median Nerve to the Radial Nerve: Branches of the *Flexor digitorum superficialis*, and the *Palmaris Longus*

The median nerve usually gives several branches to the *Flexor digitorum superficialis* at the level of the forearm, making it possible to use one of them. In addition, the *flexor carpi radialis* (FCR) can also be transferred if its use is discarded for future tendon transfers.

This technique was described by Mackinnon et al.[2] in 2002. By making an approach in the medial zone of the forearm, the *Pronator Teres* can be identified, retracting it to display the median nerve. Intraoperatively, a sensorimotor topographic identification of all components of the median nerve is performed, conducting an internal neurolysis. The branches that innervate the *Flexor digitorum superficialis* (FDS) of the third and fourth digits, the FCR and the *Palmaris Longus* are identified, supported by the use of a neurostimulator if necessary.

Also the PIN and the *extensor carpi radialis brevis* (ECRB) are identified. The neurotomy is performed as proximally as possible to facilitate its direct transfer to the anterior region of the forearm. The nerve branches of the FCR sometimes adjacent to those of the *Palmaris Longus* are transferred to the PIN, while those of the FDS are transferred to the ECRB. Prior to the transfer, electrostimulation should be used to confirm the correct functioning of the *Pronator Teres*, the anterior interosseous nerve, and the branches of the *Flexor Digitorum Profundus* (FDP). (►**Fig. 2**)

Although the authors record good results with this technique, it must be taken into account that it does not follow the principles of muscular synergy, as the donor used for wrist extension is *flexor digitorum superficialis*, which is an antagonist of the extensors. The selection of donor nerves with recipient-agonist functions facilitates their integration. In addition, the recipient for wrist extension is the ECRB, which has a highly variable origin of innervation, being able to proceed in 50% of the PIN, in 30% of the sensory branch of the radial nerve and in 20% of the bifurcation between them. This, coupled with the difficult location of the muscular belly, suggests that it is not the best option.

As an option for neurotising the PIN, they also propose using the branches of the flexor carpi ulnaris (FCU)[2].

Transfer of the Median Nerve to the Radial Nerve: Branches of the Flexor Carpi Radialis and the Pronator Teres

In 2014, a modification was published to the procedure described above, based on the transfer of a branch of the *Pronator Teres* (PT) to the *extensor carpi radialis longus* (ECRL) for the extension of the wrist, and the branch of the FCR to the PIN to restore the extension of the fingers[3]. If there were

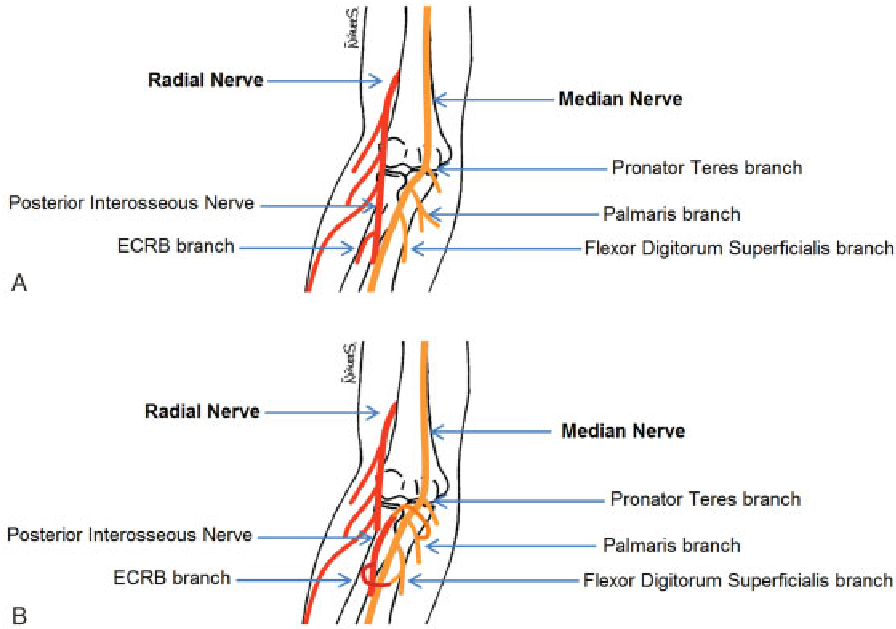

Fig. 2 A. Anatomy of radial nerve and median nerve. B. Transfer of branch of FCR (median nerve) to PIN (radial nerve), and of fascicles for third and fourth digits of superficial flexor (median nerve) to branch for ECRB (radial nerve).

no double innervation of the PT, a branch of the FDS would be used to neurotise the ECRL.

Through a single approach in the elbow flexure, the radial nerve is located in the interval between the biceps brachii and the brachioradialis. In the proximal area of the external bicipital canal, the nervous branch for the brachioradialis and the ECRL is located. The PIN is identified distally at the bifurcation with the sensory branch of the radial nerve.

In the medial area of the incision, the median nerve is exposed, located in the internal bicipital canal and its branches for the PT (usually two with a frequency close to 75%), as is the FCR, which is the longest motor branch at this level.

Among the branches innervating the PT, the longest (and usually the most proximal) is chosen and sectioned at its entrance to the PT, then being directed laterally to neurotise the ECRL branch, which is also sectioned at its origin in the radial nerve, without intraneural dissection.

The branch for the FCR is sectioned at its entrance to the muscle and directed laterally to join it to the PIN, sectioned at the level of the bifurcation with the sensory branch of the radial nerve. (►**Figs. 3** and **4**).

Median Nerve

Lesions to roots C8-D1 of the brachial plexus, known as Dejerine-Klumpke, are uncommon lesions whose

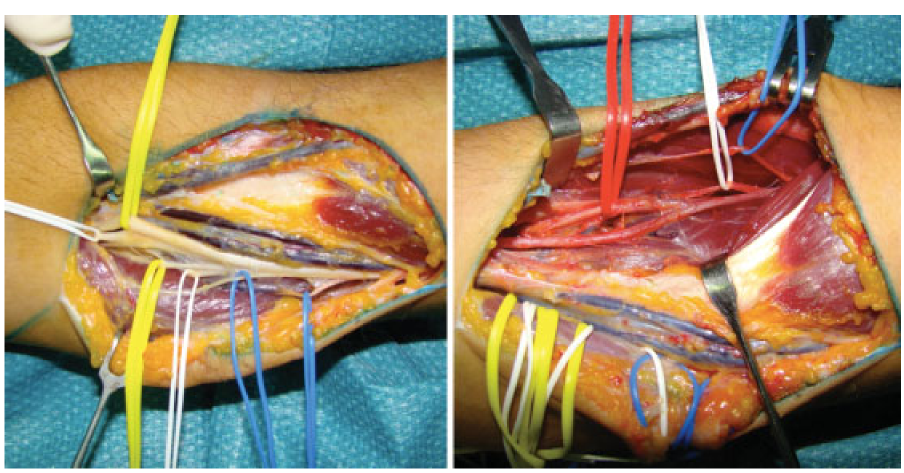

Fig. 3 To the left, transfer of round pronator branch (median nerve) to ECRL (radial nerve). To the right, transfer of FCR branch (median nerve) to PIN (radial nerve).

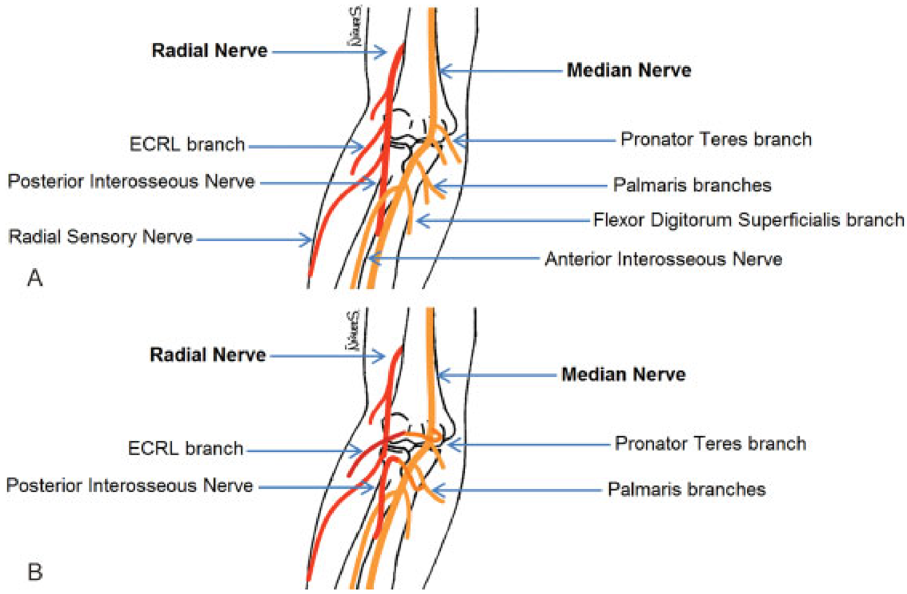

Fig. 4 A. Anatomy of radial nerve and median nerve. B. Transfer of round pronator branch (median nerve) to ECRL branch (radial nerve), and from FCR branch (median nerve) to PIN (radial nerve).

mechanism of production is traction with the abducting arm. Functionally, these types of lesions are equivalent to a medium and high ulnar palsy, with sensory loss in the territory of the ulnar nerve.

The posterior and medial fascicular groups are usually damaged, with preservation of the anterior group, mainly motor, which innervates the PT and the FCR. The medial fascicular group carries the sensory fibres, which usually remain undamaged, and the motor fibres of the hand, the muscles of which are paralysed. Finally, the posterior fascicular group is mainly motor and contains the fibres of the anterior interosseous nerve (AIN).

The priority in the treatment of this type of lesions is to recover the flexion of the fingers, so the posterior fascicular group will be the recipient of the transfers.

Anatomy

The median nerve is formed by the union of the lateral (C5-C7) and medial (C8-T1) fasciculus divisions of the brachial plexus. It descends the arm along the brachial artery, tracing the cubital fossa lateral to the biceps tendon, and passing to the forearm between the two heads of the PT. It then crosses the tendon arch and lies between the FDS and FDP, attached to the deep surface of the former. In the forearm, it innervates the PT, the FCR, and PL, and the FDS. Then the AIN emerges, together with the interosseous artery, lies between the FDP, which it innervates in its radial half corresponding to the 2nd and 3rd (and occasionally the 4th) fingers, and *Flexor pollicis longus* (FPL), to which it will also give a branch. Finally, it innervates the *Pronator quadratus* (PORQUE). The main trunk is the origin of a palmar cutaneous branch before entering the carpal tunnel. Once the nerve crosses the tunnel, it innervates the *Abductor Brevis*, the *Opponens pollicis* and *Flexor pollicis brevis*, as well as lumbricals I and II, and ends up giving the terminal sensory branches.

In 2004-2005, Zhao et al.[4,5] documented the existence of the three fascicular groups in the median nerve that have been explained previously, being the first to describe the dissection of them for the selective transfer of the phrenic nerve to the posterior fascicular group.

For fascicular identification, the nerve is located in the internal bicipital canal, between the biceps and the medial intermuscular septum or the brachialis muscle. At the level of the elbow, the antebrachial fascia, the *lacertus* fibrous and the bicipital aponeurosis are sectioned to help mobilise the nerve.

After this, a dissection of the three fascicular groups can be performed:

- The anterior group consists of the branches of the PT and the FCR: there are usually two branches for the pronator and one for the FCR, which emerge as a trident about 4 cm above the medial condyle.
- The posterior fascicular group is composed mainly of the branches of the AIN, the PL and some fine branches of the proximal region of the FDS and FDP. Its origin can be located between the lateral edge of the superficial head of the PT, and the medial border of the brachioradialis. The first of these will be the PL followed by the AIN.
- The medial fascicular group consists of the majority of the branches of the muscles of the hand and the FDS. It forms the greater part of the median nerve in the most distal zone of the arm, when the anterior and posterior fascicles have already given their branches.

In practice, it is only necessary to locate the posterior fascicle, although sometimes the medial fascicular group may also be repaired.

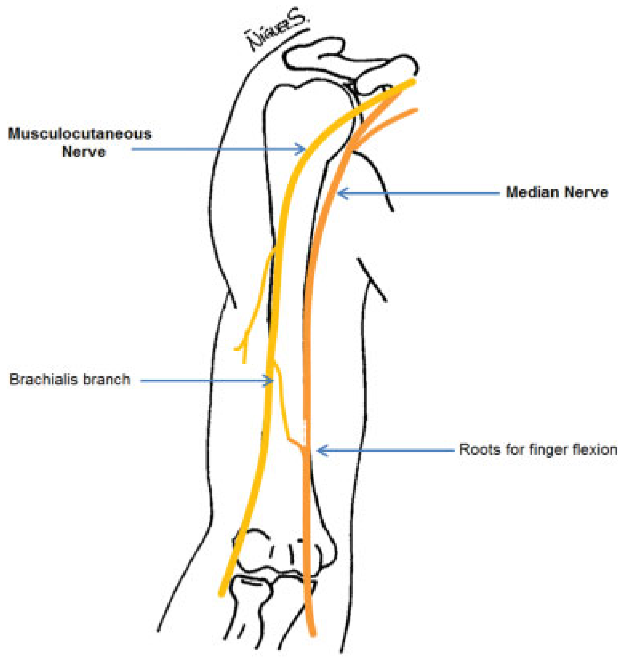

Fig. 5 Transfer of musculocutaneous nerve branch that innervates anterior brachialis to posterior fascicle of median nerve responsible for flexion of fingers.

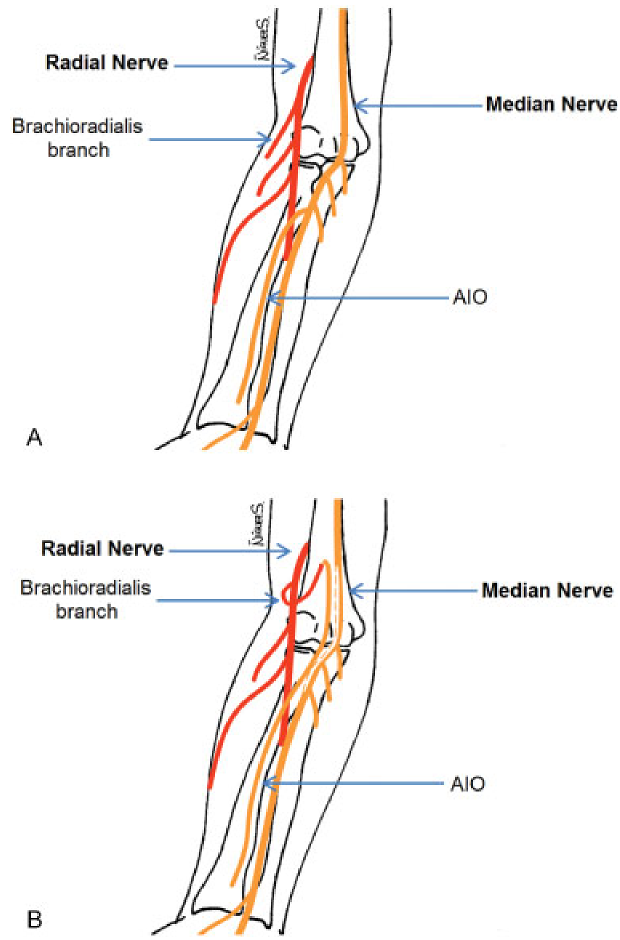

Fig. 6 A. Anatomy of radial nerve and median nerve. B. Transfer of brachioradialis nerve branch (radial nerve) to anterior interosseous nerve (median nerve).

Transfer of the Musculocutaneous Nerve to the Median Nerve: Branch of the Brachialis Muscle

In 2004, Gu et al.[6] described the transfer of the brachialis muscle branch of the musculocutaneous nerve to the posterior fascicle of the median nerve in charge of finger flexion in order to restore this function. In their anatomical study, they showed three anatomical variants: the existence of a single branch for this muscle (the most common variant), the presence of two branches (one thicker proximal and one finer distal), and a multiple pattern with more than two branches.

This procedure is performed by a single incision in the medial area of the arm. The musculocutaneous nerve is exposed, locating the brachial branch about 13 cm from the medial condyle, being dissected approximately 4 cm from the medial condyle. The median nerve is identified medial to the musculocutaneous nerve, and an intraneural dissection is performed to locate, in its posterior region, the fascicle that will be in charge of finger flexion. This dissection is extended until the fascicles can be moved without tension (►**Fig. 5**).

This procedure has a number of advantages: firstly, that it is performed with a single incision, therefore relatively easy and not very traumatic; and secondly, that the junction of the donor nerve and the recipient is performed terminus-terminal without tension. On the other hand, the drawbacks are that it is far from the target muscles, that the intraneural anatomical distribution must be relied upon and that a primary elbow flexor muscle is sacrificed.

Transfer of the Radial Nerve to the Median Nerve: Brachioradialis Branch to the Anterior Interosseous Nerve

In 2001, a technique was described that consisted of the direct transfer of a branch of the radial nerve to the Braquioradialis muscle to the AIN.[7]

An incision is made in the area of the elbow flexure. The radial nerve is located at its entrance to the interstitial canal between the biceps and the brachioradialis. In the most proximal area of the canal, the branch of the brachioradialis is located and stimulated.

The median nerve is identified in the depth of the internal bicipital canal, next to the vascular pedicle. The dissection of the median nerve is extended proximally to the junction of the middle and distal third of the arm, and distally between the two heads of the PT muscle, until the appearance of AIN and its entrance into the arch of the FDS.

The AIN is mobilised proximally by interfascicular dissection, which can easily reach the distal third of the arm in the posterior region of the median nerve, 1 cm proximal to the origin of the branch of the brachioradialis. The latter will be sectioned near its entrance to the muscle, and will be transferred to the AIN (►**Figs. 6** and **7**).

One of the main advantages of this technique is the use of a nerve branch that innervates an accessory muscle for flexion and supination of the forearm when the arm is in maximum pronation. Therefore, its denervation will not cause significant functional impotence. In addition, the transfer to the AIN may be performed more distally than the previously proposed techniques, and therefore will be

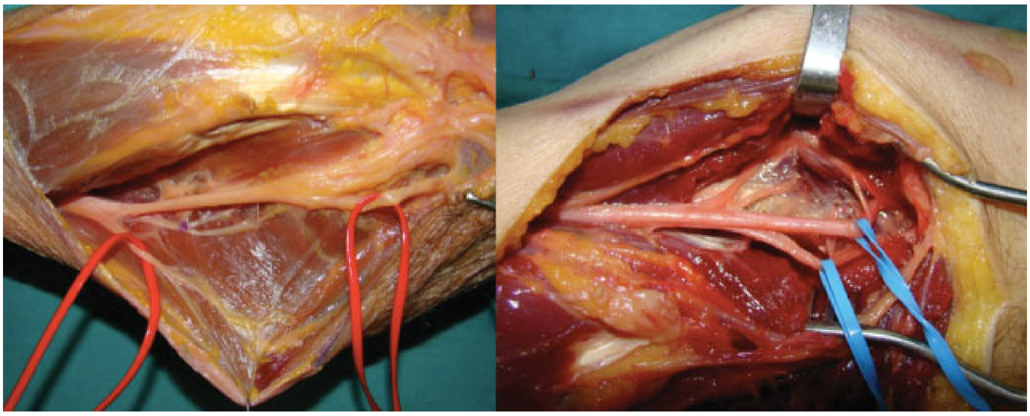

Fig. 7 Clinical image of transfer of brachioradialis nerve branch (radial nerve) to anterior interosseous nerve (median nerve).

closer to the target muscle, facilitating its reinnervation and recovery of mobility. Thirdly, it may be carried out by a single incision, which is a simple and reproducible technique, allowing the recovery of the flexion of the first three digits.

Ulnar Nerve

Ulnar nerve injuries can be very restricting, causing weakness for wrist flexion, loss of intrinsic hand function, and sensory involvement on the ulnar side of the hand.

Lesions proximal to the elbow tend to be of traumatic origin, and their approach would be similar to that of the median nerve. On the other hand, the entrapment of the ulnar nerve in the elbow is the second most frequent entrapment syndrome after the carpal tunnel syndrome (median nerve), the symptoms being similar to that described in proximal lesions, although it is characteristic of elbow pain. When the nerve injury is in the forearm, the *Flexor Carpi Ulnaris* (FCU) is preserved. Compression at the wrist and hand level is the second most common point of compression of the ulnar nerve, with the possibility of a complete (altering the sensitivity and weakness of the hand musculature) or partial lesion. The isolated lesion of the sensory dorsal branch may be traumatic or compressive. Both proximal and distal lesions, in their evolution, are manifested with the characteristic 'claw hand' due to weakness of interosseous and lumbrical muscles.

Anatomy

The ulnar nerve originates from the medial Fascicle of the brachial plexus (C8-D1). It is a mixed nerve that runs in the arm along with the median nerve and medial to the brachial artery, passing through the medial aponeurotic septum to the posterior compartment, and continuing up to the ulnar canal at the elbow. Here, it gives the first branches to the FCU and part of the FDP corresponding to the fourth and fifth digits. It passes through the humeral and ulnar heads of the FCU, settling below the FDP up to the wrist, where it gives sensory branches for the hypothenar eminence, the ulnar zone of the dorsum of the hand, and the fourth and fifth fingers. It reaches the Guyon channel between the pisiform and hamate bones, to continue as a motor nerve of the muscles of the hypothenar and thenar eminences, interosseous muscles and lumbricals.

Under examination, we observed Froment's sign due to weakness of the *Adductor pollicis* and atrophy of the interosseous muscles, especially the first one, and of the hypothenar eminence. Sensitivity will be altered in the fifth finger and ulnar half of the fourth, as well as the ulnar half of the palm and back of the hand to the wrist.

Transfer of the Median Nerve to the Ulnar Nerve: Anterior Interosseous to the Motor Branch of the Ulnar Nerve

Transfer of the AIN to the motor branch of the ulnar nerve to restore the intrinsic function of the hand was first performed in 1991 by Mackinnon,[8,9] being described later by other authors with slight variations, since it is the only one that has achieved the reinnervation of the intrinsic hand muscles. (►**Fig. 8**)

The approach is performed 6-7 mm ulnar to the thenar crease of the hand, proceeding to open the Guyon canal, making a careful dissection to avoid the section of the palmar cutaneous branch of the median and ulnar nerves. Upon reaching the crease of the wrist, the approach is extended proximally by a zigzag incision. As it advances, the ulnar nerve is released ulnar to proximal and the antebrachial fascia is opened, as if the palmaris brevis muscle is present. Once the ligament is open, the neurovascular bundle is separated to medial in order to allow exposure of the ulnar nerve in the hand. It is necessary to palpate the hook of the hamate for guidance, since this is where the deep motor branch of the ulnar is reflected to radial and dorsal, settling under the hypothenar musculature. Next, the muscular fascia of the hypothenar eminence is identified and is traced proximally to its free edge, just in the area ulnar to the hook of the hamate. This is where the motor branch of the ulnar separates from the rest of the nerve. Once found, the branch is decompressed until it reaches the flexor digiti minimi brevis. It is very important to release the nerve of the free edge of the hypothenar fascia to achieve good nerve regeneration.[10] At this point, the response deficit by this motor branch will be checked again by nerve stimulation.

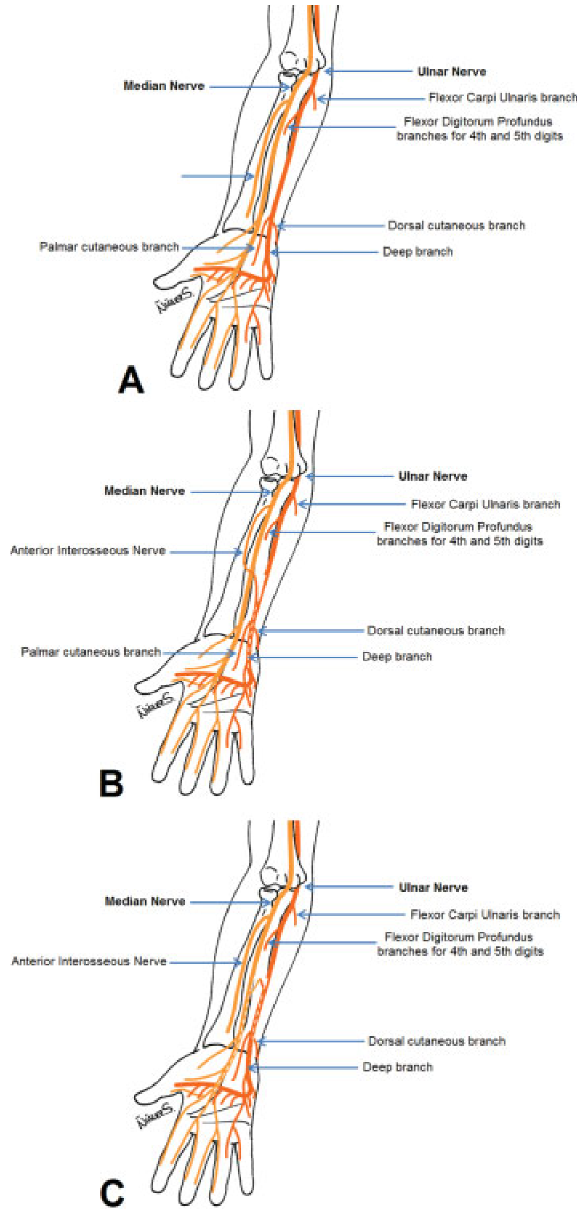

Fig. 8 A. Anatomy of median nerve and ulnar nerve. B. Transfer of anterior interosseous nerve (median nerve) to motor branch of ulnar nerve. C. Transfer of sensory branch for third interdigital space (median nerve) to dorsal cutaneous branch of ulnar nerve.

The incision is then extended proximally, tracing the ulnar nerve in the forearm and locating the division between the motor and the sensory fascicular group. The latter will be on the radial side of the ulnar nerve. The fascicle corresponding to the motor branch of the ulnar nerve rests on the ulnar side of the sensory component, and the dorsal cutaneous branch will be on the ulnar side of the motor branch (leaving a sensory-motor-sensory arrangement). Sometimes there is a small blood vessel arranged longitudinally in the epineurium marking the division between the different components. Intraneural nerve dissection is performed from the hamate to the proximal area, where only the motor fasciculus will be sectioned, to avoid unnecessary handling of the nerve and to reduce the time of surgery.

The AIN can be found deep in the central area of the forearm, along with its accompanying vessel, entering the PQ muscle. First, the PQ muscle will be identified by separating the flexor tendons to radial in order to identify the muscle to the most ulnar zone. The neurovascular bundle can be identified in the proximal and central area of the muscle. The nerve is carefully separated from the bundle and the intervention continues inside the muscle to gain several centimetres in length. The nerve begins to give branches in the central portion of the muscle, and here it will be sectioned and mobilised proximally to transfer it to the ulnar nerve. Similar to how the AIN is sectioned in the most distal area, it is very important that the motor branch of the ulnar nerve is sectioned sufficiently proximal so that it can be mobilised and attached to the AIN without tension in any position of the wrist or fingers. This point is usually located about 9-10 cm proximal to the wrist. Satisfactory results are gained with this result, even though the AIN contains less nerve fibres than the deep motor branch of the ulnar (►**Fig. 9**).

It is also possible to recover ordinary sensitivity by transferring the palmar cutaneous branch from the median nerve to the sensory fascicle of the ulnar border of the hand that is located at the most radial part of the nerve, taking into account that recovery can appear even two years after the transfer[11]. Prolonged trauma to an anaesthetised area due to denervation may lead to ulceration of the skin and other comorbidities. To avoid this, it is advisable to associate a sensory transfer to the motor repair.

Sensory ulnar reinnervation may also be achieved by a terminus-terminal transfer of the fascicle of the third interdigital space, innervated by the median nerve. Once the median nerve is located in the distal area of the forearm, the sensitive component of the third interdigital space may be identified similarly to how the ulnar nerve was previously identified, since there is a plane delimited by a blood vessel. If this plane cannot be clearly identified, the median nerve should be traced to the hand by fully opening the transverse carpal ligament to identify the branches when they begin to separate from the main nerve component. The motor branch will be traced proximally to the forearm, without the need to perform the neurolysis thereof, as we have explained in the case of the ulnar motor branch. The sensory branch of the median nerve is sectioned distally, proximal to the proximal border of the carpal tunnel, to ensure a tension-free junction. This fascicle is then taken proximally to transfer it to the sensory component of the ulnar nerve. It is recommended to do so approximately 5-6 cm proximal to the wrist to avoid the joint.

Musculocutaneous Nerve

Elbow flexion is the most important restorative function in a paralytic arm. The Brachialis muscle is the main flexor of the elbow, while the biceps is a supinator muscle which, secondarily, cooperates in flexion. Thus, a complete lesion of the musculocutaneous nerve produces significant weakness of elbow flexion, especially with the supinated arm, and altered sensitivity at the radial border of the forearm.

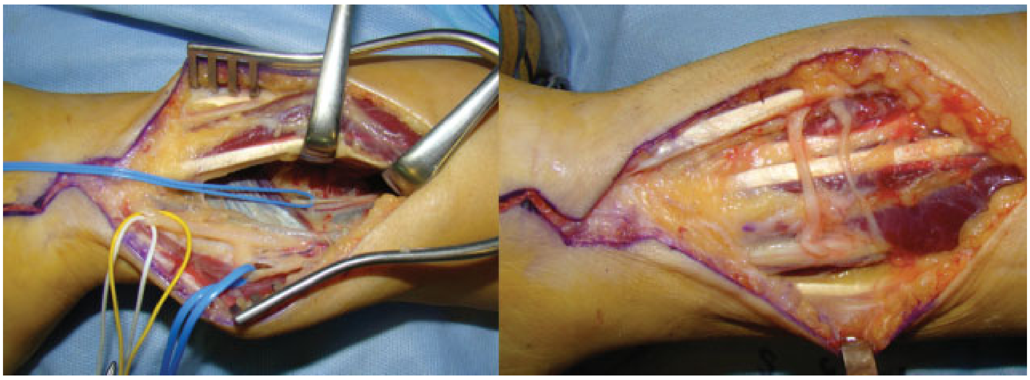

Fig. 9 On the left, the anterior interosseous (blue) is introduced into the pronator square, in the lower part we can see the fascicular division of the ulnar dorsal sensory branch (blue), motor branch (white) and sensory branch (yellow). On the right image of double nerve transfer: anterior interosseous to motor branch and cutaneous palmar to sensitive branch.

Unlike the radial nerve, isolated paralysis of the musculocutaneous nerve is rare. It can occur exceptionally in trauma and humeral fractures. Compressions can occur more frequently in the coracobrachialis muscle with certain sporting activities.

Anatomy

The musculocutaneous nerve emerges from the external division of the lateral fasciculus of the brachial plexus (C5-C7). It pierces the coracobrachialis muscle, innervating it, and from there it passes to the intermuscular plane between the biceps and the brachialis, which it innervates. It then exits the fascia of the brachialis, and in the forearm it becomes subcutaneous, resulting in the lateral antebrachial cutaneous nerve, which innervates the radial edge of the anterior face of the forearm.

Therefore, lesion of the musculocutaneous nerve will produce a deficit of elbow flexion, in addition to reducing the supinating force provided by the biceps brachii, and a sensory deficit that is usually lower than expected, due to the anastomosis that it presents with the sensory branch of the radial nerve.

Transfer of Ulnar and Median Nerves to the Musculocutaneous Nerve

This procedure was described in 1994 by Oberlin et al.[12] relating the transfer of a fascicle of the ulnar nerve at the bicipital branch of the musculocutaneous nerve. Given the great flexor power of the brachialis muscle, this technique was modified in 2003 by Mackinnon et al.[13] who developed a transfer of two fascicles, using branches of the median and ulnar nerves to reinnervate the branches of the musculocutaneous nerve for the biceps and the Brachialis.

The approach is performed in the central portion of the bicipital canal, dissecting the interval between the triceps and the biceps. The ulnar nerve is located medial to the brachial artery, while the median nerve is lateral to it. The musculocutaneous nerve is identified on the deep and medial surface of the biceps, after palpation. The branch or branches for the biceps originate in the more proximal zone and pass more laterally, while the branch or branches for the anterior brachial emerge distally and head more medially while entering deeper into the muscle. Both are sectioned in the proximal area, at their point of origin, and are taken to the medial area where they join the median and ulnar nerve. The donor fascicle is selected by proximity, although usually the bicipital branch is close to the median nerve, and the brachial branch to the ulnar nerve (►**Figs. 10** and **11**). A nerve stimulator is used to identify the redundant fascicles of the median nerve that innervate the FCR and those of the ulnar nerve for the flexor carpi ulnaris muscle (FCU). Alternatively, fascicles of the flexor digitorum superficialis and the pronator teres may be used as a donor of the median nerve.

At present, it is highly disputed whether this double neurotization is necessary and it is advisable to perform a single wrist flexor fascicle neurotization to a branch of the biceps brachii. With this isolated neurotization, good elbow flexion is achieved and the motor deficit that is usually left after the use of a medial fascicle is avoided.

Extraplexal Neurotizations

Spinal Accessory Nerve

This is one of the most popular nerve transfers and the first described in literature, back in 1913 by Tuttle.[14] It is mainly used for neurotizations of the suprascapular nerve. It is approached in the posterior triangle of the neck, with the nerve on the anterior surface of the trapezius muscle. The search for the proximal nerve can be initiated at the junction between the upper and middle thirds of the sternocleidomastoideus muscle, and its distal portion at the junction of the middle and lower thirds of the trapezius,[15] even though there are other techniques for its location.[16]

Bertelli and Ghizoni[17] described what may be the simplest and most reliable technique for harvesting the accessory nerve in the neck. At the anterior margin of the trapezius, the cervical fascia of the muscle is separated in a zone proximal to the clavicle, at approximately 3-4 cm, as this is where the accessory nerve is more superficial and, therefore, more easily identifiable. Viewing the motor branches entering the muscle may help with its location. Before sectioning, it is advisable to stimulate it electrically to ensure its integrity.

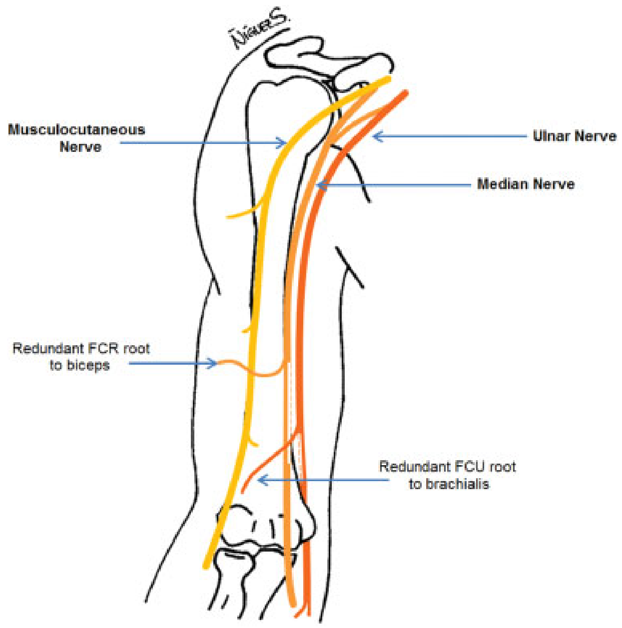

Fig. 10 Transfer for musculocutaneous nerve. Redundant fracture of FCU (ulnar nerve) for biceps brachii. Redundant fascicle of FCR (median nerve) for anterior brachial.

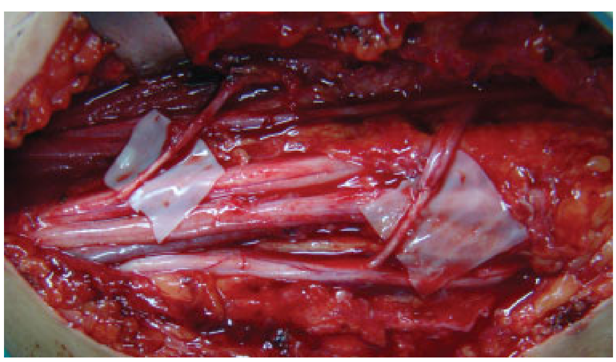

Fig. 11 Double nerve transfer for musculocutaneous: to the left fasciculus of median to biceps and the fascicle of cubital to anterior brachial. Between the medial and ulnar is the brachial artery.

It will be sectioned as distally as is necessary to achieve direct contact with the recipient nerve without pressure. If the trapezius is removed, the nerve may be dissected up to the upper and medial angle of the scapula. The trapezius will then be reinserted into the clavicle and the acromion.

Phrenic Nerve

This is used for neurotizations of the suprascapular nerve, the musculocutaneous nerve and the median nerve. Good results have been reported in literature for the treatment of brachial plexus injuries, although it should not be used as a donor for reconstructions in children under one year of age, or when simultaneously using intercostals. This nerve is located constantly on the anterior surface of the anterior scalene muscle, with a lateral to medial trajectory, using a supraclavicular approach, and dissecting the nerve proximally until the appearance of the root C5,[15] although its approach varies according to the nerve to which it will be transferred.

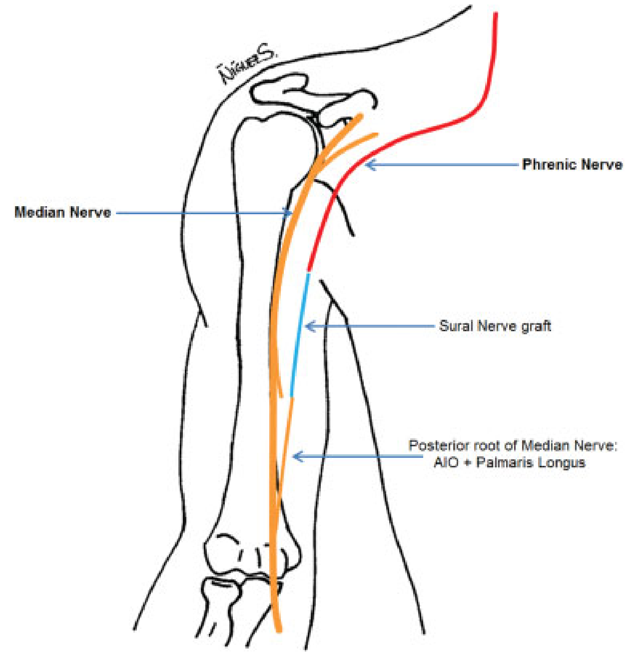

Fig. 12 Transfer of phrenic nerve to posterior fascicle of the median nerve, with sural nerve graft.

Transfer of the Phrenic Nerve to the Median Nerve

Described in 2004-2005, Zhao et al.[4,5] Prior to approaching the phrenic nerve, thorax X-rays are performed in maximal inspiration and exhalation to exclude possible nerve injury. Pulmonary function tests and an electrocardiogram are also performed. The incision is made on the fifth rib, from the midaxillary line to the lateral area of the sternum. The lower periosteum of the rib and the adhered pleura are opened to reach the pericardium, on the side of which are the phrenic nerve and the pericardiacophrenic artery and vein. The nerve is gradually separated from the pleura in order to mobilise it, from its entrance into the diaphragm, where it will be sectioned up to the apex of the thoracic cavity. A new incision is made between the anterior axillary line and the second intercostal space, and a third incision in the axilla, from where the nerve will be recovered. From the axillary incision to the arm, the nerve will be passed through the subcutaneous tissue. Once transferred, the gap between the end of the phrenic nerve and the AIN will be measured, and a sural nerve graft will be used to connect the two (►**Fig. 12**).

This nerve transfer is very uncommon nowadays.

Intercostal Nerves

These have been used especially for musculocutaneous nerve neurotizations. Such procedures must be performed without interposed grafting to obtain a better result, so dissection should be performed as distally as possible. The approach is performed along the lower border of the pectoralis major from the anterior axillary fold to the sternum. The pectoralis major is dissected and rejected upwards. The pectoralis minor is found beneath, and its lateral border is used as a reference point to identify the third, fourth and fifth ribs, which are desensitised, identifying the nerve at the lower edge of the rib at the level of the intercostal muscles.[14]

Upper Cervical Roots

The anterior primary branches of the C3 and C4 cervical roots (both or only one), immediately distal to the phrenic nerve, are used. This transfer is especially indicated in obstetric brachial plexus palsy. An incision is made at the posterior border of the sternocleidomastoideus muscle to expose the supraclavicular plexus, and the C3 and C4 root is dissected at the foraminal level. Dissection must be meticulous, with electrical stimulation, given the great variation in the anatomy of the brachial plexus.[18]

Contralateral C7 Nerve Root

The C7 root redundantly innervates the muscles also nourished by the C8 and D1 roots, so the proposal is to use C7 on the healthy side as an axon donor to the paralysed plexus. Sacrifice of this root implies a very mild triceps paralysis, not clinically evident in most cases.[19] It is necessary to dissect the healthy C7 contralateral root with an anterior cervical approach, as well as the injured nerve, and the ulnar nerve with its vascular pedicle up to the wrist, since it is used as a graft by placing it in a subcutaneous tunnel between the contralateral C7 root and the nerve to be neurotised.[15] This is a complex technique with multiple associated risks, so its use has been limited to carefully selected patients with concomitant lesions of the phrenic nerve and the spinal accessory nerve.

Hypoglossal Nerve

Poor functional results are obtained with the transfer of the hypoglossal nerve to the brachial plexus, whereas hypoglossal-facial anastomoses are usually successful. It is performed by an incision that begins 2 cm posterior and 2 cm below the gonion (junction point between the ascending bundle and the body of the mandible), and extends distally in the submaxillary region. The platysma is dissected and the anterior belly of the digastric muscle is identified. Below this is the hypoglossal muscle, very close to the carotid artery.[15]

Conflicts of interest
Authors declare no conflicts of interest.

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