NEW NERVE TRANSFERS FOLLOWING PERIPHERAL NERVE INJURIES

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High nerve injuries in the upper extremity present the surgeon with challenging reconstructive situations. The relatively slow rate of peripheral nerve regeneration and the inexorable pace of motor end-plate loss create physiological limitations to restoration of extremity function by high anatomic reconstruction. The concept of nerve transfer seeks to avoid the time/distance constraints on anatomic reconstruction by transferring distal donor motor or sensory axons to injured nerves close to the affected end organs. Several nerve transfer options and the authors' experience with motor and sensory restoration are presented.

KEY WORDS: nerve transfer, peripheral nerve injury, upper extremity, motor end plate, neurotization

The clinical situation of high nerve injury in the upper extremity has been a challenging problem for reconstructive surgeons because of intrinsic biological constraints on successful restoration of function. The principal functional limitations occur because motor end plates become refractory to reinnervation after approximately 1 year in adult patients.[1] Given the known rate of neuronal regeneration following injury (1-1.5 mm/d), the regeneration distance beyond which recovery is doubtful is approximately 12 to 15 inches. This time limit may be extended in younger patients. Clinical studies have clearly documented the inverse relationship between height of injury and prognosis for function.[2-4]

Common clinical scenarios include closed brachial plexus injuries and open trauma to the radial, median, or ulnar nerves and branches about the elbow. The resultant distal deficits have been treated with immediate or delayed tendon transfers,[5,6] sometimes as "internal splints" in anticipation of later regeneration.[7] Tendon transfers are based on the concept that the rerouting of an active functional unit will return motion to a paralyzed joint. Nerve transfers carry this concept further, to include sensory rehabilitation as well. Functional continuity is thus established in the absence of anatomic integrity.

Nerve transfer to peripheral nerves injured at proximal levels seeks to maximize functional outcome by decreasing the distance/time element of neural regeneration, and by increasing specificity of donor inflow. In essence, nerve transfers attempt to convert high nerve injuries to low nerve injuries, hopefully to reflect the more favorable prognosis and time to recovery of low nerve injuries.

Nerve transfer is a management philosophy that is based upon the following principles. (1) *Preservation of the motor end plate:* return of motor function is dependent upon time and distance. After approximately 12 months or 12-15 inches of denervation, the end-plate becomes refractory to reinnervation.[8] This limitation defines one primary consideration in designing nerve transfers: donor nerves are transected distally at their muscular insertions, then coapted to recipient nerves as close as practicable to the recipient end-plate. This shortens the distance, and the time, to end-organ reinnervation. (2) *Avoidance of nerve grafting:* nerve grafting introduces an extra repair site interface for regenerating units to cross. This theoretically increases misdirection and dropout of regenerating units proceeding distally. Correctly designed ipsilateral nerve transfers generally do not require nerve grafts; if grafts are required, they are short. Chuang has recently shown the clinical utility of nerve transfer principles in 99 adult and obstetrical brachial palsy patients, achieving consistently good outcomes in transfers performed without nerve grafting. Transfers requiring interpositional grafts did not achieve similarly satisfactory results.[9] (3) *Dedicated function.* fascicular plexus formation is maximal at the level of the spinal roots and decreases distally.[10,11] Therefore, grafting at the cervical root level will increase the chances of sensorimotor and antagonistic muscle group fiber mixing. In contrast, distal nerve transfers provide relatively pure motor or sensory axons. The medial pectoral nerve provides strong motor drive to the musculocutaneous nerve without notable functional deficits.[12] Oberlin has had excellent results with transfer of normal ulnar nerve fascicles to the immediately adjacent musculocutaneous nerve, without resultant ulnar deficits.[13] The thoracodorsal nerve will easily reach suprascapular, axillary, and lateral cord elements without interpositional nerve grafts and without tension. Many other transfers are of course feasible. Experience has shown that, while recommended,

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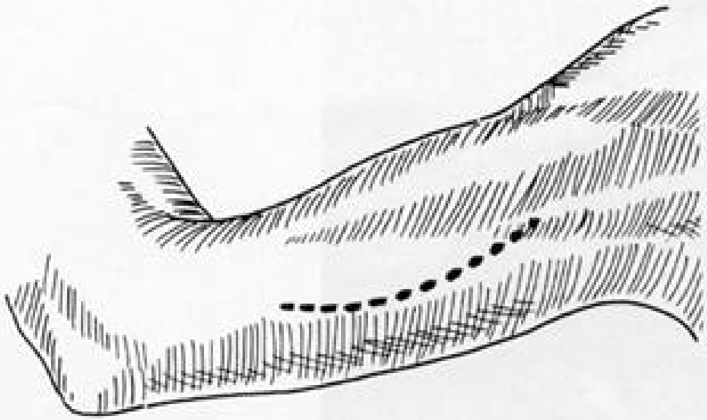


Fig 1. Surface marking for musculocutaneous nerve exposure. Right arm, medial view. Incision is placed over the palpated interval between biceps and triceps muscles.

CLINICAL EXAMPLES

Musculocutaneous Nerve Injury

A common problem seen after closed trauma to the upper extremity is loss of elbow flexion. The difficulty in evaluating this injury is that it is often multilevel, at the level of the brachial plexus, and again at the entry point of the nerve into the biceps muscle where the arrangement of fascia combined with the angle of the nerve entry tend to tether the nerve and make it susceptible to a second traction injury. Because of the frequency of distal injury, we believe that assessment of the musculocutaneous nerve at the level of the biceps muscle is necessary. In addition, the application of nerve transfer principles directs that management should take place at this level.

We have historically used branches of the medial pectoral nerve to provide motor flow into the musculocutaneous nerve.[12] We have also recently started to use the method of Oberlin in transferring a portion of the adjacent normal ulnar nerve to musculocutaneous nerve motor fascicles, and believe that this is an excellent procedure that will become increasingly important in biceps functional reconstruction.

Description of Procedures

Medial pectoral nerve transfer to musculocutaneous nerve. An incision is placed in the medial arm along the palpated interval between the biceps and triceps muscles, in the proximal and middle third of the arm (Fig 1). This incision is carried anteriorly into the axilla within any convenient skin crease. A superior extension into the distal deltopectoral groove is usually required for adequate retraction of the pectoralis major muscle and exposure of medial pectoral branches. Deep dissection is started in the arm incision down to the sheath of the neurovascular bundle containing the brachial artery and the adjacent branches of the brachial plexus. Next, the biceps belly is retracted laterally, exposing its undersurface. The musculocutaneous nerve is seen entering the middle third of the biceps belly as it runs along the midline of the muscle (Fig 2).

The musculocutaneous nerve is followed distally into the substance of the biceps muscle where it is neurolysed externally and then protected with a vessel loop. Dissection proceeds distally into the muscle, until the motor branches to the biceps muscle are seen to turn laterally into the muscle mass (Fig 3A). The fibers of the lateral antebrachial cutaneous (LABC) nerve are seen to continue distally, closely applied to the undersurface of the biceps. The motor portion of the musculocutaneous nerve is dissected free from LABC fibers with internal neurolysis. The musculocutaneous nerve is directly stimulated with 1 to 2 mAmp of current from a handheld nerve stimulator to confirm lack of motor response.

Attention is now turned to the axilla where the axillary

Fig 2. Exposure of medial pectoral and musculocutaneous nerves in the arm. Left arm, medial view. MP: medial pectoral nerves; MC: musculocutaneous nerve; U: ulnar nerve; M: median nerve. Note proximity of MC to MP nerves. (Reprinted with permission.[12])

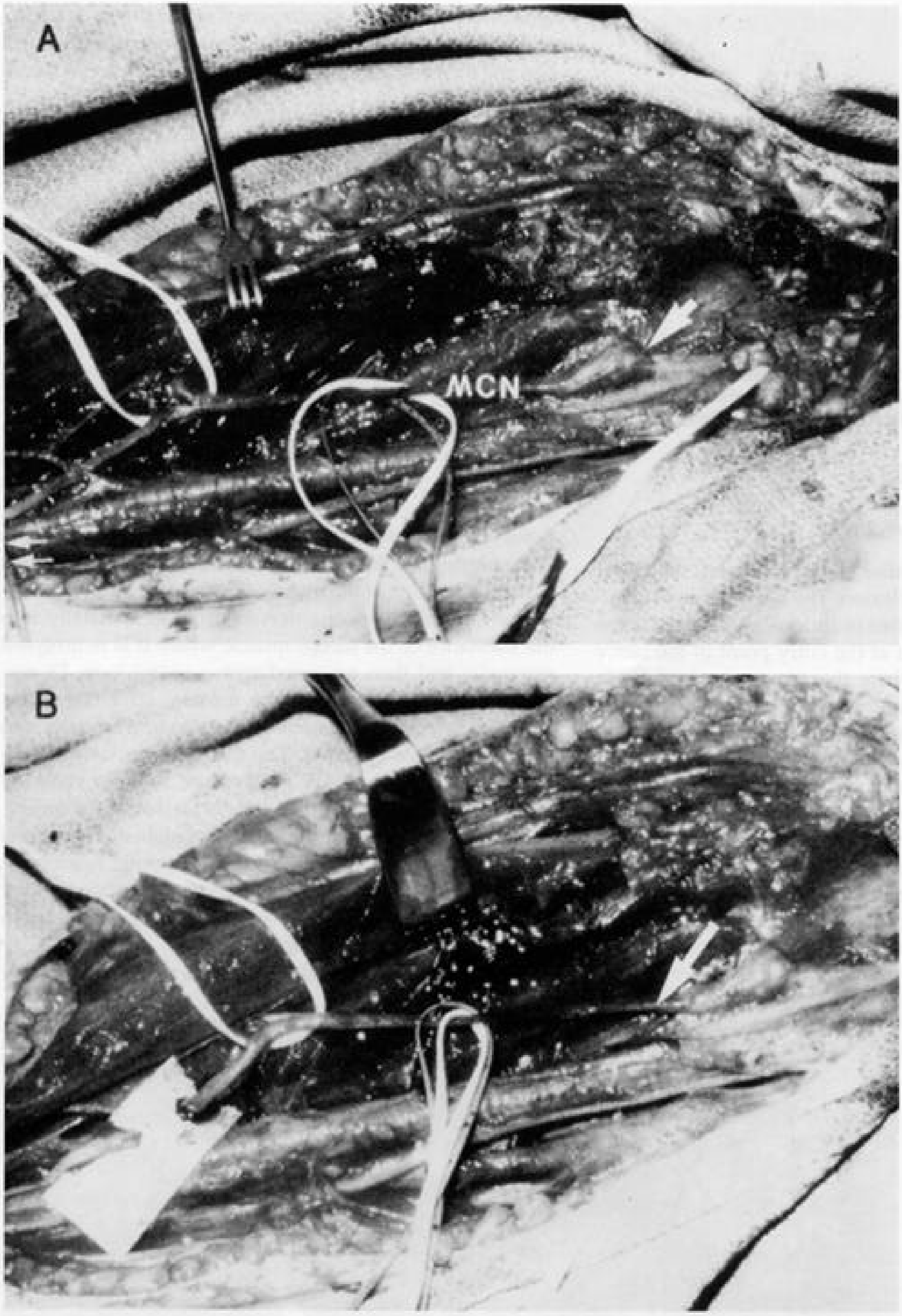


Fig 3. (A) Entry of musculocutaneous nerve into biceps brachii muscle. Right arm, medial view. Distal loop surrounds motor branch. Arrow signifies site of repair of medial pectoral to musculocutaneous transfer. (B) Transection of lateral antebrachial cutaneous nerve just distal to bifurcation from motor branch. Right arm, medial view. Distal loop surrounds motor branch. Transected lateral antebrachial cutaneous branch sits on pale background distally.

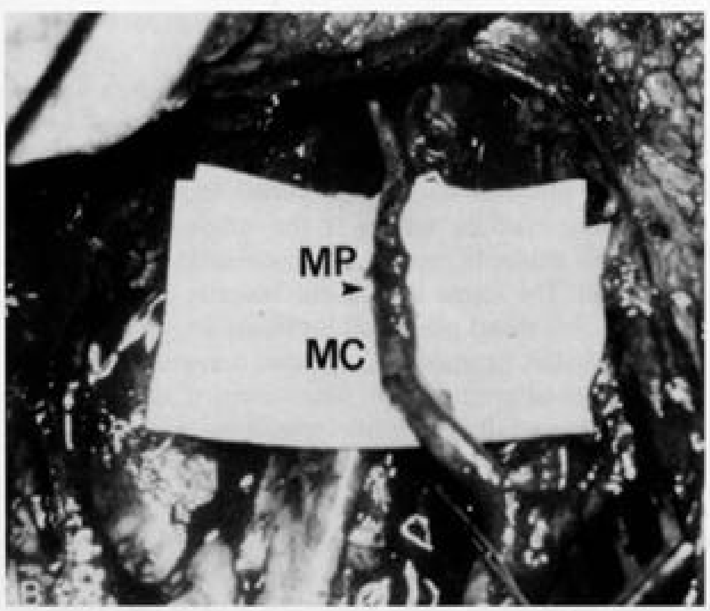
and deltopectoral groove incisions are developed to the level of the underlying fascia. Superior retraction of the pectoralis major muscle will allow clear visualization of the fine neurovascular bundles comprising the end branches of the medial pectoral nerve as they travel within a distinct layer of mixed adipose and areolar tissue (Fig 2). Direct stimulation with a handheld stimulator at 2 mAmps will confirm that these branches are functional. The nerve tion to the musculocutaneous nerve. Generally two to four branches are identified for use in the transfer.

At this point, the musculocutaneous nerve is transected as close to the muscle as possible while retaining sufficient length for tension-free coaptation to the medial pectoral branches. Several centimeters of epimysial dissection is possible before the nerve actually becomes intramuscular at the midpoint of the length of the biceps. A piece of suture

Fig 3 (cont'd). (C) Transposition of lateral antebrachial cutaneous nerve into biceps muscle adjacent to motor branch entry point. Right arm, medial view. Arrow points to site of intramuscular transposition of lateral antebrachial cutaneous nerve. (Reprinted with permission.[12])

nerve proximally with intraneural dissection to the level of the lateral cord. This is preferable to interpositional nerve grafting. Standard microsurgical coaptation is then performed (Fig 4). It is sometimes necessary to release the tendon of the pectoralis major muscle to achieve this proximal dissection, and the tendon should be reconstructed before closure.

Because the transfer takes place proximal to the separation of the LABC nerve, some motor inflow from the medial pectoral nerves will be lost through the fibers of the LABC branch (Fig 3A). To recapture this otherwise lost motor drive, the LABC is transected immediately distal to its branch point from the motor portion of the musculocutaneous nerve (Fig 3B) and then transposed directly into



the muscle, immediately adjacent to the area of entry of the motor fascicles (Fig 3C). This neurotization maneuver has been shown to result in recovery of clinically useful motor function.[14]

We have used this procedure in approximately 15 patients in the past 7 years with M4 or greater recovery in about two-thirds of this group at 2 years follow-up. Approximately half of these patients have been operated upon in the last 2 years, and therefore the overall success rate should turn out to be higher. Initial clinical recovery is typically seen at 6 to 8 months following surgery, and recovery continues for a further 2 years in most cases.

Ulnar nerve fascicle transfer to musculocutaneous nerve (Oberlin procedure). Technical aspects of the procedure are based upon the description by Oberlin et al.[13] The musculocutaneous nerve is identified and dissected in a manner similar to that described above. However, the arm incision does not require extension into the axilla or deltopectoral groove (Fig 1). Secondly, the nerve transfer to the musculocutaneous nerve is performed more distally, past the branch point of the LABC nerve, so that pure motor fascicles are isolated for dedicated functional transfer. This also obviates the requirement for LABC neurotization back into biceps muscle. Once the motor fibers of the musculocutaneous nerve are identified and protected distal to the branch point of the LABC, direct stimulation with a handheld nerve stimulator at 2 mAmps is performed to confirm lack of motor response. The motor branch to the biceps is transected immediately distal to the takeoff of the LABC, and transposed to the region of the ulnar nerve (Fig 5A and 5B).

The ulnar nerve is identified by entering the fascia surrounding the brachial neurovascular bundle and dissectsuture is used to measure the appropriate length of ulnar nerve that will easily transpose to the transected end of the musculocutaneous motor branch.

At the appropriate measured distance, the epineurium of the ulnar nerve is entered with straight microscissors, and fascicle groups are dissected and separated as in intraneural neurolysis. Loupe magnification of at least 4.0 × is essential. A useful instrument is the 5-inch Jacobson hemostat that has very fine tips and is well-suited for fascicle separation and isolation. We have found that anteromedial fascicles are relatively free of plexus formation at this level, and have sufficient duplication of function that transection and transposition of a single fascicle group does not result in functional disturbance of the ulnar nerve. Two fascicle groups, generally those most medial and anterior in position, are then stimulated at 1 mAmp current with a handheld nerve stimulator. Each fascicle group will contain three to five fascicles. Stimulation of each group will elicit a similar contraction of the flexor carpi ulnaris and sometimes the ulnar finger flexors and intrinsics. The fascicle group giving the weaker response to stimulation is selected for transfer. As described by Oberlin et al, this usually amounts to 10% or 15% of the volume of the ulnar nerve. After transection of the appropriate fascicle group, it is neurolysed proximally until transposition to the musculocutaneous motor branch is easy and without tension.

The transected ulnar fascicle is transposed to the musculocutaneous stump and sutured end-to-end with 10-0 suture under microscope guidance. Meticulous hemostasis is obtained and the wound is carefully closed. We immobilize the arm in adduction and 90° elbow flexion for 3 weeks postoperatively and thereafter encourage motion at the elbow and shoulder.

In our experience with seven patients using this technique we have seen no ulnar nerve deficits in sensibility or in motor strength. We have seen initial biceps motor return within 3 to 6 months, but these patients are all only 2 to 8 months out from surgery. Final outcome probably is greatly influenced by the time from injury to operation. We have used similar fascicular transfers in other cases in which a portion of a normally functioning nerve is transferred to an injured nerve. For example, ulnar nerve fascicles to triceps branch in one patient, radial nerve fascicles to triceps branch in one patient, and posterior cord fascicles to axillary nerve in four patients; these patients are 1 to 6 months out from surgery and therefore too early to assess. The principles and techniques are the same as described for the Oberlin procedure.

Pronator Teres Branch/Anterior Interosseous Nerve Palsies

Brachial plexus neuritis or trauma high in the arm often result in partial loss of median nerve motor function. We have seen three patients with deficits of the pronator teres[15] or anterior Interosseous nerves.[16] In these cases, our strategy is to restore inflow by anterior transposition of the ulnar nerve and transfer of its flexor carpi ulnaris branches to the adjacent terminal branches of pronator teres[17] or anterior interosseous nerve (AIN).

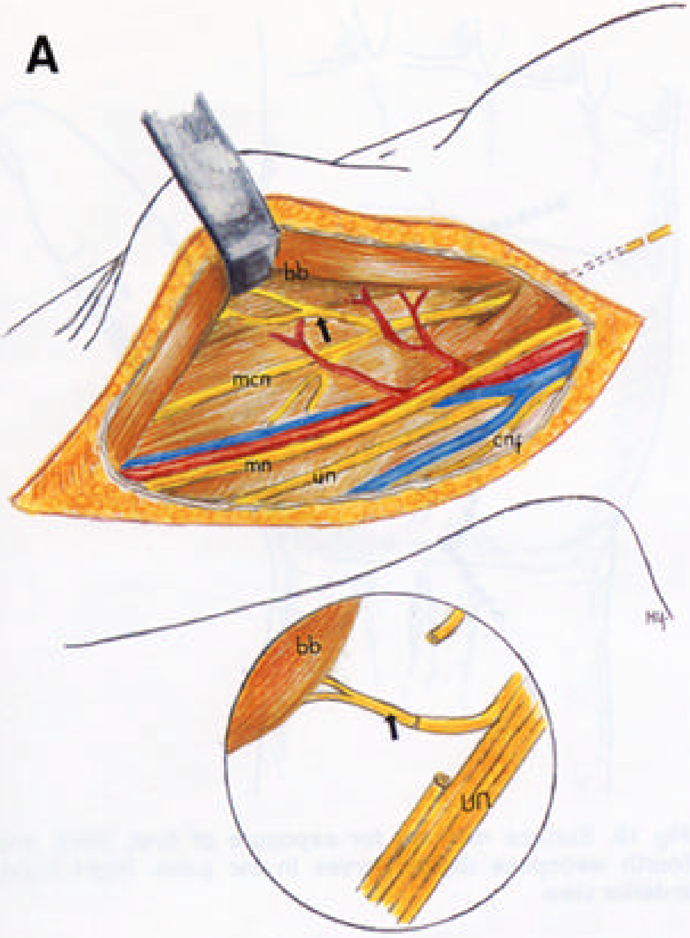
Description of procedure. Surgery is performed under tourniquet control. First, a volar forearm incision is made 1 to 2 cm distal to the elbow crease and extended 6 cm distally in a sigmoidal fashion (Fig 6). Sharp dissection is carried down through the interval between the brachioradialis muscle belly and the common flexor mass. In the case of the branch to pronator teres, the pronator muscle is retracted radialward and the branch is seen entering the midportion of the muscle (Fig 7).

The AIN is located about 3 cm distal to this level and can be dissected freely as it exits the main median nerve into the belly of the flexor digitorum profundus mass. The pronator branch or AIN is transected as distally as possible while retaining sufficient length to be coapted to the flexor carpi ulnaris (FCU) branches of the ulnar nerve without the use of a nerve graft.

Next, attention is turned to the ulnar side of the arm. An incision is placed anterior to the medial epicondyle, extending proximally to the distal one third of the arm over the basilic vein and distally over the flexor carpi ulnaris (Fig 8). The suface marking of the basilic vein is in the distal two thirds of the medial arm, one fingerbreadth below the interval between the biceps, and the triceps muscle bellies. The incision is carried distally 8 to 10 cm past the medial epicondyle over the flexor carpi ulnaris muscle belly.

The medial antebrachial cutaneous nerve is identified proximally where it is adherent to the basilic vein and encircled with a vessel loop. Fascia from the medial head of triceps to the medial intermuscular septum is incised, and the ulnar nerve is encircled with a vessel loop. This fascia is then released for 8 cm proximally. The medial intermuscular septum is excised; division of it is not sufficient. Then the roof of the cubital tunnel is split distally. The ulnar nerve may be lifted from the postcondylar groove and any proximal motor branches to the flexor carpi ulnaris are dissected distally and preserved to gain length for the transposition (Fig 9). An epineurectomy is done now, and if necessary, an internal neurolysis also. A step-cut to lengthen the flexor pronator muscle is outlined and cut. The common flexor tendon, which is the origin of the flexor digitorum sublimis muscle, is completely divided deep and distal. The fascia is back-cut laterally and distally if needed. This distal piece will be sutured to the proximal, medial one left attached to the medial humeral epicondyle. The periosteal origin of the flexor carpi ulnaris from the ulna is released distally while protecting the ulnar nerve. The ulnar nerve is transposed anteriorly to lie on the

Fig 5. (A) Exposure of musculocutaneous nerve at entry into biceps brachii muscle. Right arm, medial view. bb: biceps brachii muscle; mcn: musculocutaneous nerve; mn: median nerve; un: ulnar nerve; cnf: cutaneous nerve to forearm. Arrow points to motor branch of mcn distal to branching of lateral antebrachial cutaneous nerve. Detail shows schematic of ulnar nerve fascicle



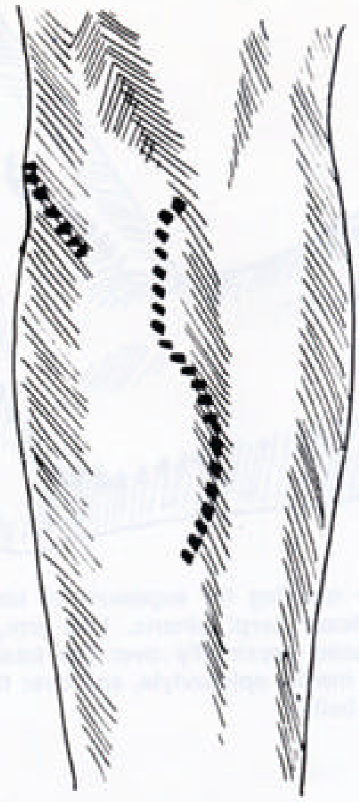
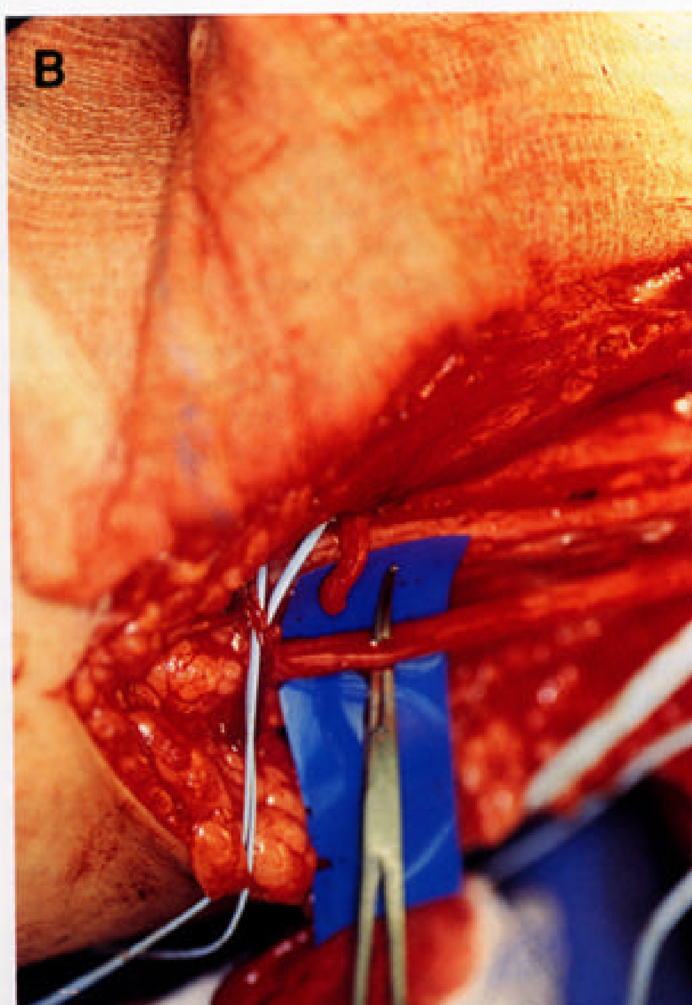
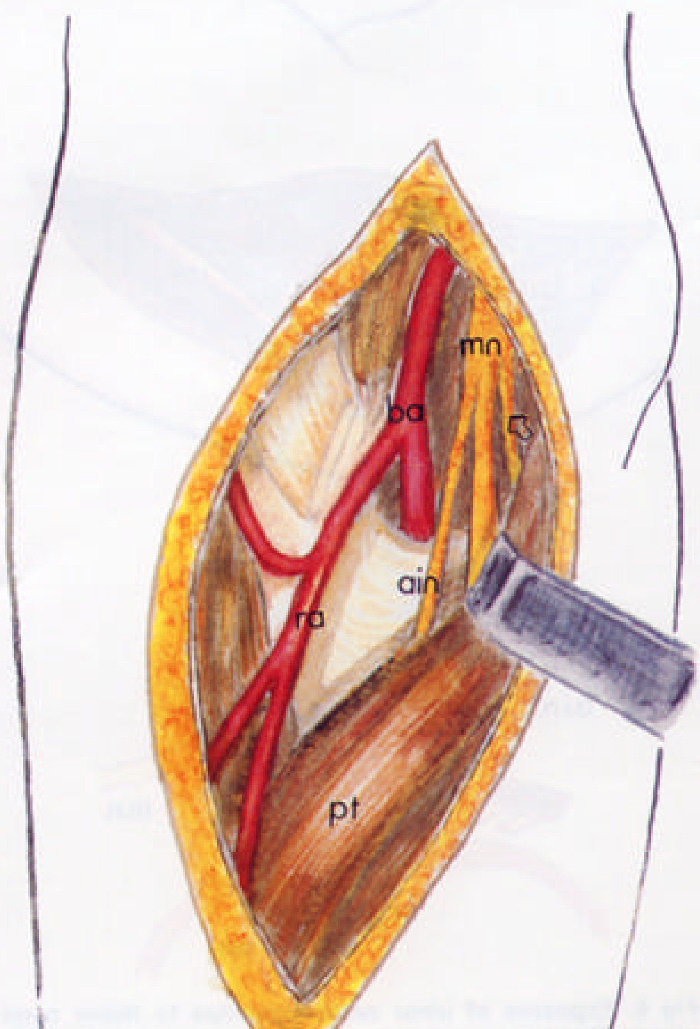


Fig 6. Surface marking for exposure of anterior interosseous nerve and median nerve branch to pronator teres. Left arm, anterior view. The incision is placed in the palpated interval between brachioradialis and flexor muscle masses.





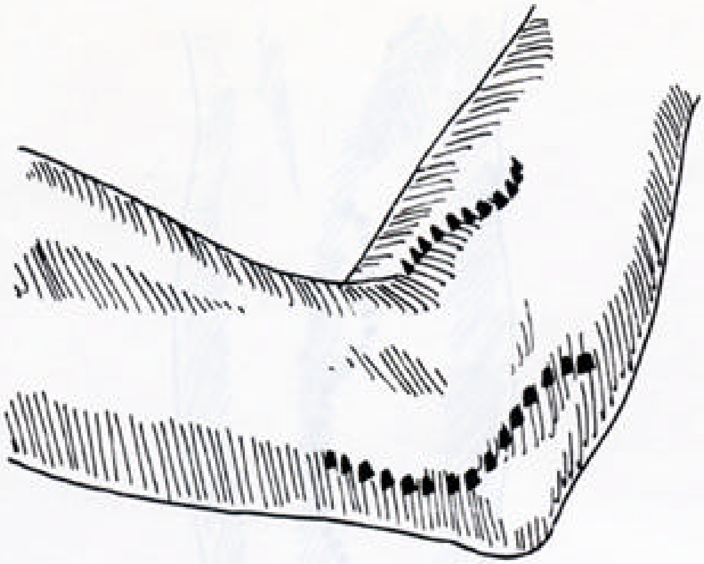


Fig 8. Surface marking for exposure of ulnar nerve and branches to flexor carpi ulnaris. Left arm, medial view. Incision is placed proximally over the basilic vein, then anterior to the medial epicondyle, and over the flexor carpi ulnaris muscle belly.

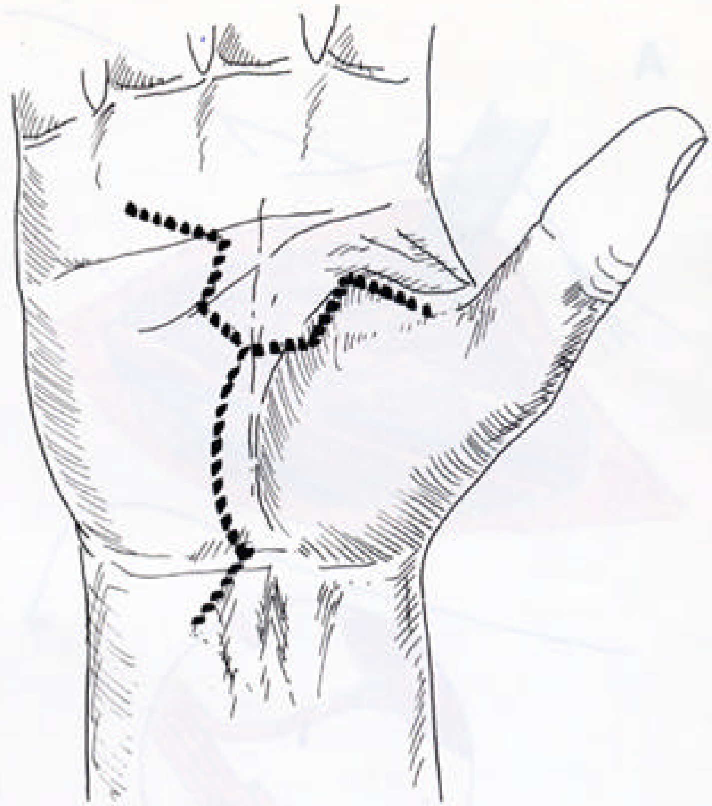


Fig 10. Surface marking for exposure of first, third, and fourth webspace digital nerves in the palm. Right hand, anterior view.

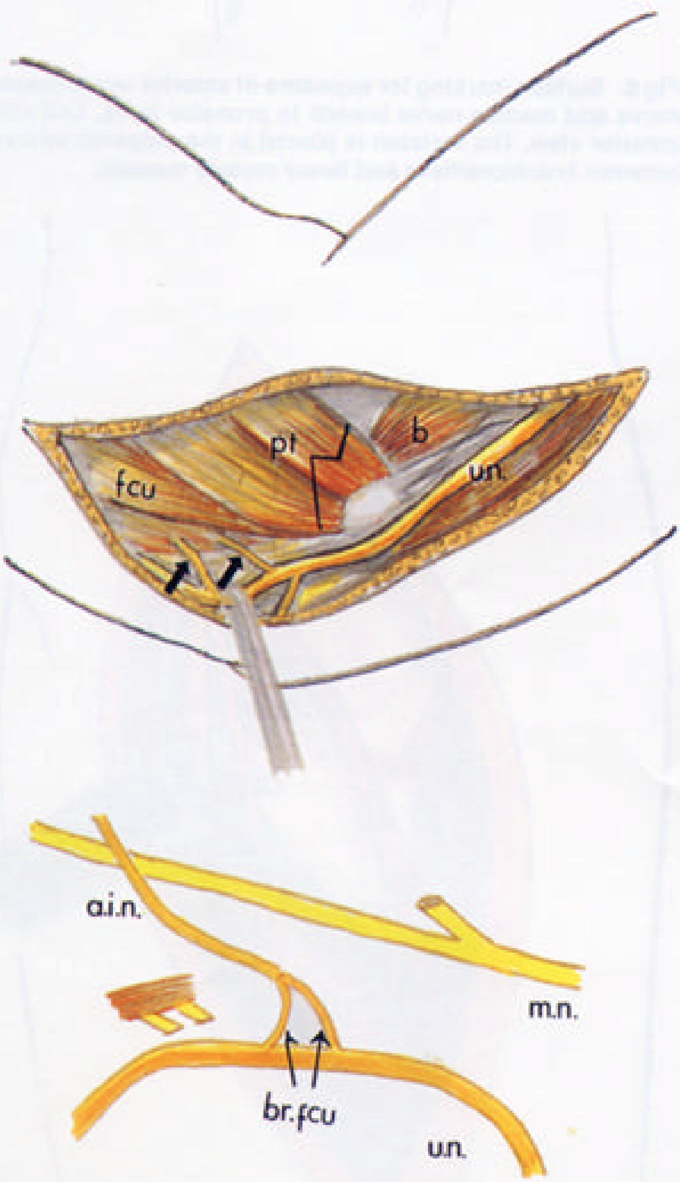


Fig 9. Exposure of ulnar nerve branches to flexor carpi

brachialis muscle. The branches to the FCU are again identified. These three or four branches are dissected free and two of them are transected as distally as possible. The FCU branches are now transposed radially to the site of AIN or pronator branch (Fig 9), then coapted under microscope magnification with 9-0 or 10-0 suture. Arm adduction with 90° elbow flexion is maintained for 3 weeks, followed by aggressive range of motion therapy at the shoulder and elbow.

The patient with pronator palsy recovered M4+ motor strength by 5 months following surgery. The two AIN patients are 3 and 4 months out from surgery and have shown early clinical signs of recovery at this point.

Thumb/Index Webspace Sensory Loss

High injury to the median nerve results in loss of sensibility to the thumb and index finger, the most important touch and pinch digits. During the several months to years that regenerating axons can require to bridge the distance from injury to end organ, the hand is severely disabled in its inability to perceive touch and pain. In addition to lack of utility for environment-testing and object-handling, the fingers are at risk for undetected injury and ulcer formation.

To provide sensibility in a more timely fashion, a transfer of the ulnar-innervated common digital nerve from the fourth (ring/small finger) webspace to the first webspace common digital nerve is planned. In cases of median nerve fascicular injury in which only the first webspace is

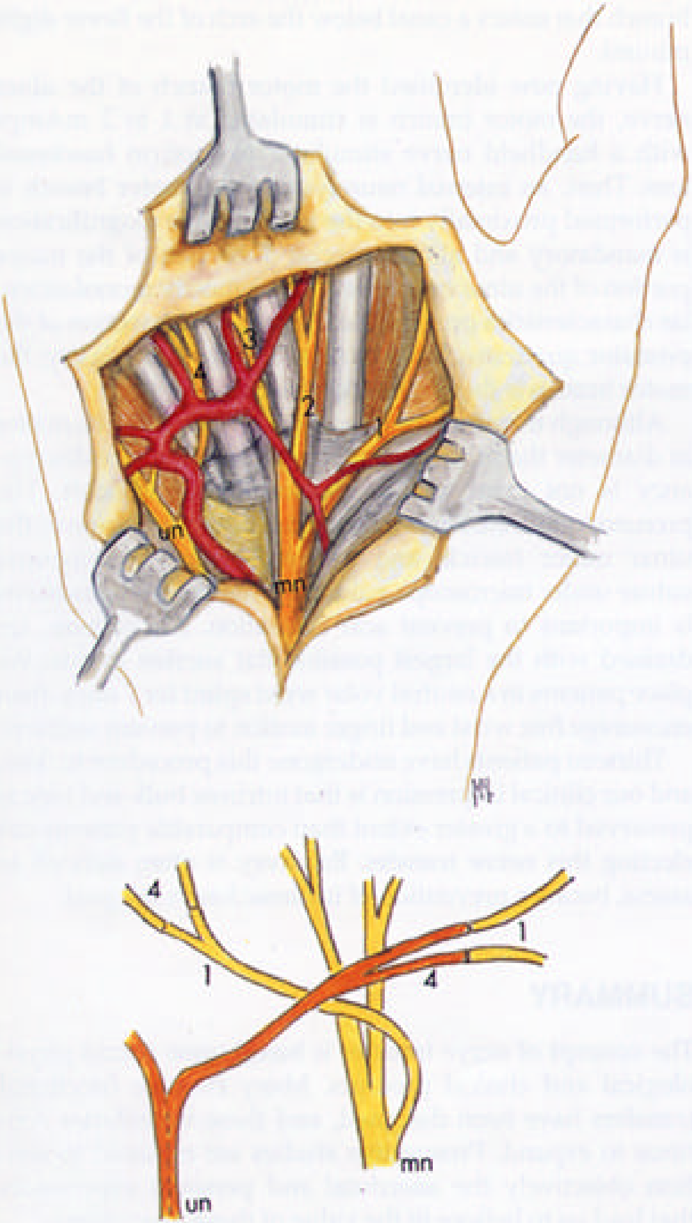


Fig 11. Exposure of first and fourth webspace nerves in the palm. Right hand, anterior view. Numbers denote webspace branches; un: ulnar nerve; mn: median nerve.

Description of procedure. A carpal tunnel release incision is made along a line connecting the palmaris longus tendon to the third webspace in the palm. The incision starts at the distal wrist crease and curves parallel to the thenar eminence but generally along the described line for a distance of 6 to 7 cm where it is extended distally in a V-fashion into both first and fourth/third webspaces, using zigzag incisions (Fig 10). Sharp dissection reveals the neurovascular bundles supplying the webspaces. The common digital nerves are bluntly separated from the adjacent vessels, and traced distally to the level of the volar webspace crease. By this point, the proper digital nerves

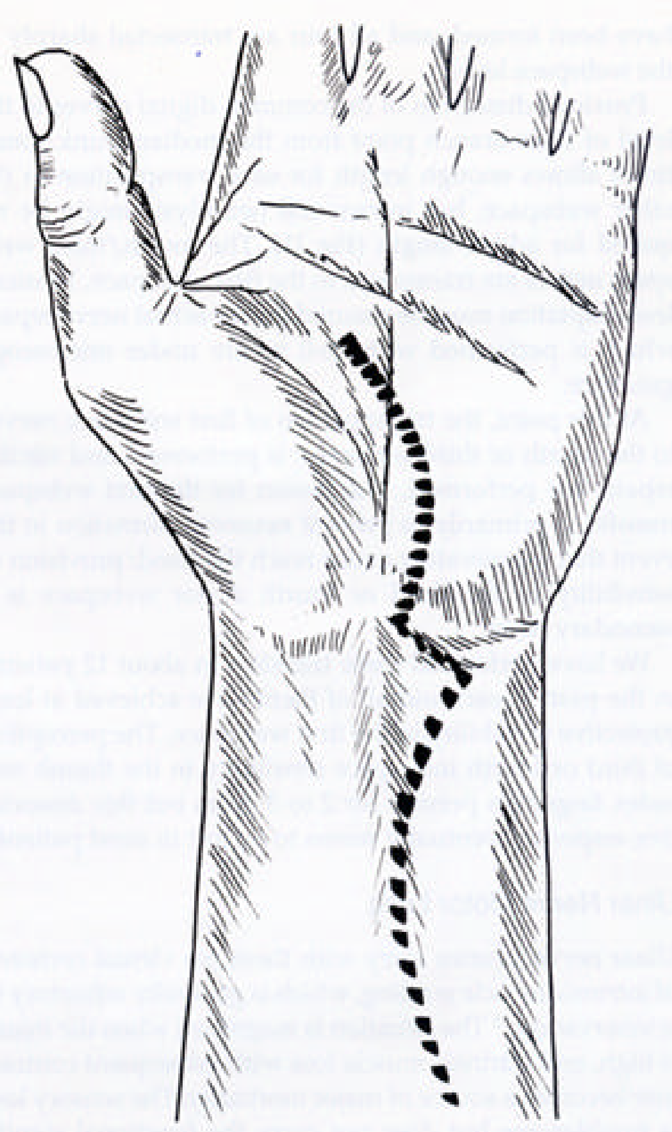


Fig 12. Surface marking for exposure of ulnar nerve motor branch and median nerve branch to pronator quadratus. Left hand, anterior view.

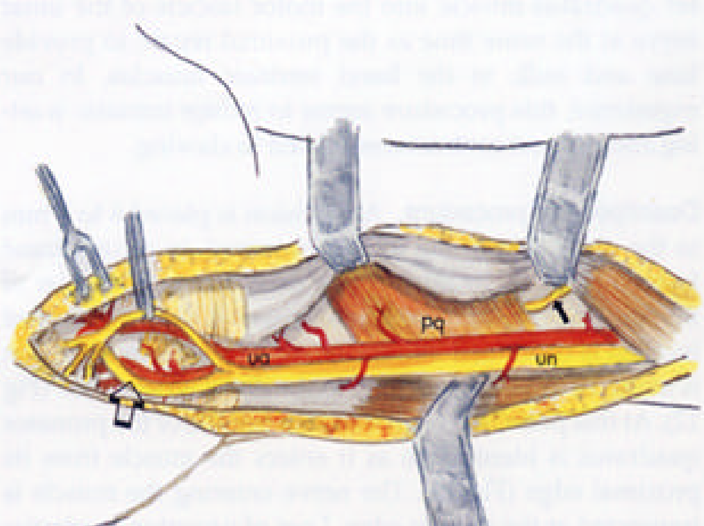


Fig 13. Exposure of ulnar nerve motor branch and median nerve branch to pronator quadratus. Right arm, anterior view. ua: ulnar artery; pq: pronator quadratus; un: ulnar nerve.

have been formed, and all four are transected sharply at the webspace level.

Proximal dissection of the common digital nerves to the level of their branch point from the median trunk sometimes allows enough length for easy transposition to the other webspace, but intraneural neurolysis might be required for added length (Fig 11). The fourth/third webspace nerves are transposed to the first webspace. Tensionless coaptation must be assured before actual nerve repair, which is performed with 10-0 suture under microscope guidance.

At this point, the transposition of first webspace nerves to the fourth or third webspace is performed, and similar repairs are performed. The reason for the first webspace transfer is primarily to prevent neuroma formation in the event that regenerating axons reach the hand; provision of sensibility to the third or fourth donor webspace is a secondary issue.

We have performed these transfers in about 12 patients in the past 7 years and all of them have achieved at least protective sensibility in the first webspace. The perception of third or fourth interspace sensibility in the thumb and index fingertips persists for 2 to 3 years but this dissociative response eventually seems to be lost in most patients.

Ulnar Nerve Motor Loss

Ulnar nerve injuries carry with them the virtual certainty of intrinsic muscle wasting, which is generally refractory to reinnervation.[18] The situation is magnified when the injury is high, and intrinsic muscle loss with subsequent contracture becomes a source of major morbidity. The sensory loss is troublesome but does not carry the functional significance of the motor deficit.

In the situation of a high ulnar nerve injury, we prefer to transfer the median-innervated motor branch of the pronator quadratus muscle into the motor fascicle of the ulnar nerve at the same time as the proximal repair, to provide tone and bulk to the hand intrinsic muscles. In our experience, this procedure seems to reduce intrinsic wasting and prevent contractures related to clawing.

Description of procedure. An incision is placed 6 to 7 mm to the ulnar side of the thenar eminence, in a curvilinear fashion along an imaginary line from the radial border of the ring finger to the distal wrist crease. A zigzag or curved incision is continued into the forearm, where an extension is made 12 to 14 cm proximal to the distal wrist crease (Fig 12). At this point, the neurovascular bundle of the pronator quadratus is identifiable as it enters the muscle from its proximal edge (Fig 13). The nerve entering the muscle is transected at the muscle edge. Loss of pronator quadratus function has no identifiable consequences.

Next, attention is turned to the ulnar nerve in the palm. The ulnar neurovascular bundle is exposed by careful dissection through the soft tissue overlying Guyon's canal. The ulnar artery and accompanying veins are retracted ulnarly, taking with them the sensory branches of the

branch that enters a canal below the arch of the flexor digiti minimi.

Having now identified the motor branch of the ulnar nerve, the motor branch is stimulated at 1 to 2 mAmps with a handheld nerve stimulator to confirm functional loss. Then, an internal neurolysis of the motor branch is performed proximally into the wrist. Loupe magnification is mandatory and allows precise dissection of the motor portion of the ulnar nerve that retains mostly monofascicular characteristics proximal to the area of transection of the pronator quadratus branch. Allowing for some laxity, the motor branch is then transected sharply.

Although the pronator quadratus branch is often smaller in diameter than the ulnar motor branch, the size discrepancy is not great and coaptation is not difficult. The pronator quadratus nerve is coapted without tension to the ulnar motor fascicle and repaired with 9-0 epineurial suture under microscope guidance. Meticulous hemostasis is important to prevent scar formation. All patients are drained with the largest possible flat suction drains. We place patients in a neutral volar wrist splint for 7 days, then encourage free wrist and finger motion to prevent stiffness.

Thirteen patients have undergone this procedure to date, and our clinical impression is that intrinsic bulk and tone is preserved to a greater extent than comparable patients not electing this nerve transfer. Recovery is often difficult to assess, because prevention of intrinsic loss is the goal.

SUMMARY

The concept of nerve transfer is based upon sound physiological and clinical precepts. Many creative functional transfers have been designed, and these boundaries continue to expand. Prospective studies are required to confirm objectively the anecdotal and personal experiences that lead us to believe in the value of these procedures.

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