

Targeted Muscle Reinnervation in the Upper Extremity Amputee: A Technical Roadmap

Michael S. Gart, MD,* Jason M. Souza, MD,* Gregory A. Dumanian, MD*

Targeted muscle reinnervation (TMR) offers the potential for improved prosthetic function by reclaiming the neural control information that is lost as a result of upper extremity amputation. In addition to the prosthetic control benefits, TMR is a potential treatment for postamputation neuroma pain. Here, we present our surgical technique for TMR nerve transfers in transhumeral and shoulder disarticulation patients. (*J Hand Surg Am.* 2015;40(9):1877–1888. Copyright © 2015 by the American Society for Surgery of the Hand. All rights reserved.)

Key words Myoelectric, neuroma, neurotization, prosthesis, targeted muscle reinnervation.

TARGETED MUSCLE REINNERVATION (TMR) employs a series of nerve transfers to provide intuitive prosthetic control to upper extremity amputees. Targeted muscle reinnervation has yielded improved prosthetic outcomes in high upper extremity amputees.^{1,2} In addition to the prosthetic control benefits, TMR is a potential treatment for postamputation neuroma pain.³ Because TMR is most frequently performed in the transhumeral and shoulder disarticulation patient, the surgical approach to TMR at these amputation levels serves as the focus for this review.

To be most effective, TMR requires a patient with a major amputation proximal to the wrist and without a more proximal nerve injury. These procedures require close coordination between the surgical, prosthetic, and rehabilitation teams. Targeted muscle reinnervation also has potential for wider applications such as neuroma prevention or control, with the only requirement being a patient in reasonable health with an unrepairable nerve injury. The procedure is

not technically demanding and does not require extensive diagnostic aids or advanced instrumentation. There is minimal surgical morbidity, enabling the procedure to potentially be performed in the outpatient setting.

PREOPERATIVE CONSIDERATIONS

We consider TMR an option in any patient with a major upper extremity amputation proximal to the wrist who wishes to improve prosthetic function. At this point, management of postamputation neuroma pain remains a secondary indication for TMR, pending further evaluation by an ongoing randomized controlled trial.⁴ Age has not seemed to influence TMR success rates of neurotization, although it is well established that nerve transfers in younger patients probably have better outcomes overall.⁵

The pattern of nerve transfers should be dictated by the availability of donor nerves and muscle targets rather than the skeletal anatomy. This is a significant departure from consideration of the bones and joints as the prime determinants of operative procedure. As such, a very proximal transhumeral amputee will likely be treated with a “shoulder disarticulation” pattern of nerve transfers, and a patient with intact elbow but lacking forearm muscle targets would be considered for a “transhumeral” style TMR. The mechanism of injury, residual limb length, presence of residual muscles still able to be contracted at will, the presence and location of scars on the residual limb, and the location of Tinel signs are important as

From the *Department of Surgery, Division of Plastic and Reconstructive Surgery, Northwestern Memorial Hospital, Chicago, IL.

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Corresponding author: Gregory A. Dumanian, MD, Division of Plastic and Reconstructive Surgery, Northwestern University, Feinberg School of Medicine, 675 North St. Clair St., Galter Suite 19-250, Chicago, IL 60611; e-mail: GDumanian@nmh.org.

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preoperative markers of potential donor nerve lengths and availability of muscle targets. A long residual limb has the advantage of greater donor nerve length and more available muscle targets to serve as transfer recipients. Longer donor nerves will allow for more aggressive nerve trimming while still achieving a tension-free coaptation, maximizing the likelihood that healthy fascicles are transferred. For the conventional pattern of TMR nerve transfers, transhumeral patients must demonstrate voluntary biceps and/or triceps function, and shoulder disarticulation patients should demonstrate voluntary contraction of the pectoralis, serratus, and latissimus dorsi muscles. In the absence of viable muscle targets, free muscle transfers can be combined with TMR, but a more detailed discussion of this approach is beyond the scope of this review.^{6,7} Finally, residual limb soft tissue quality should be assessed before surgery. Whereas TMR is most easily accomplished within a healthy soft tissue envelope, the technique can be performed in combination with pedicled flaps, tissue expansion, or other methods aimed at improving the quality and contour of the residual limb. Lastly, TMR requires unimpaired nerve function proximal to the level of the nerve transfer. Therefore, patients with proximal brachial plexus or spinal cord injuries represent a notable contraindication to the procedure. Eliciting voluntary contraction of the pectoralis major muscle serves as a gross maneuver to exclude a dense brachial plexopathy.

TRANSHUMERAL LEVEL

Surgical rationale

As initially developed, TMR in the transhumeral amputee was designed to create novel “hand close” and “hand open” control signals, while preserving native elbow flexion and extension signals. Elbow flexion and extension signals are maintained by preserving musculocutaneous innervation of the long head of the biceps and radial innervation of the long head of the triceps, respectively. The “hand close” signal is accomplished via transfer of the remnant median nerve (MN) to the motor nerve of the short head of the biceps brachii. The “hand open” signal results from transfer of the distal radial nerve to the motor nerve of the lateral head of the triceps. In a patient with a long residual limb, transferring the remnant ulnar nerve (UN) to the brachialis muscle can create a fifth control signal that is often allocated to wrist control. Using “direct control” algorithms, this approach enables intuitive control of 5 unique prosthetic functions.⁸ In light of recent advances in

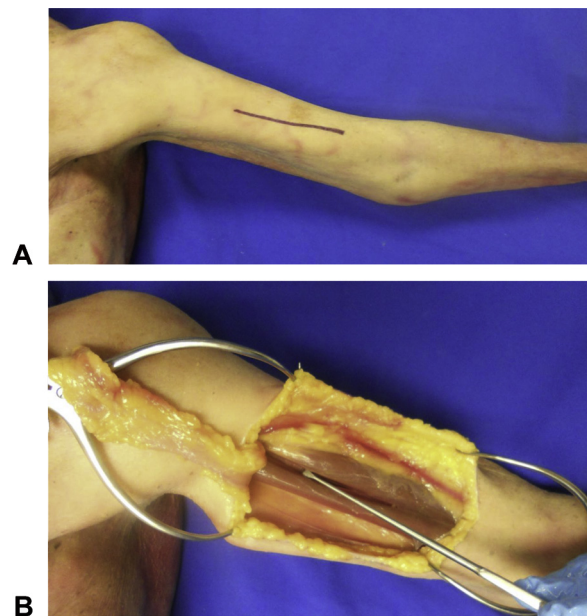


FIGURE 1: **A** Anterior incision along the biceps raphe. **B** Elevation of the skin flaps and the proximally based adipofascial flap.

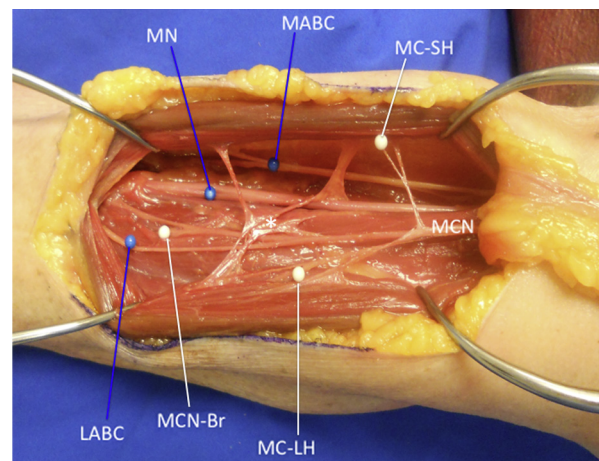


FIGURE 2: Left arm viewed from the head shows the anterior exposure of the MCN and MN. Note the branching of the distal MCN just proximal to the crossing of the consistently observed vascular arcade (*). LABC, lateral antebrachial cutaneous nerve; MCN-Br, motor branch to the brachialis muscle; MCN-LH, motor branches to the long head of the biceps; MCN-SH, motor branches to the short head of the biceps.

prosthetic control algorithms, “pattern recognition” can now utilize the neural information salvaged by these nerve transfers to produce as many unique functions as can be performed by the terminal device (Hargrove et al, presented at the 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2013).

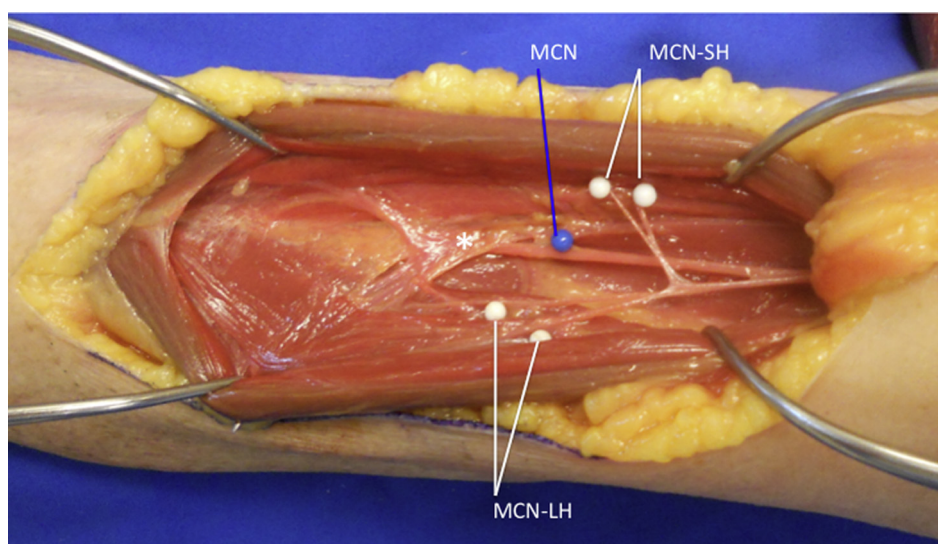


FIGURE 3: Left arm viewed from the head shows exposure of the MCN in the biceps brachii midline raphe (retracted). Note the vascular arcade (*). MCN-LH, motor branch to the long head of the biceps; MCN-SH, motor branches to the short head of the biceps.

Surgical technique

In the preoperative holding area, the sites of any Tinel signs over the MN, radial nerve (RN), and UN end neuromas are marked, as are the imagined raphe between the heads of the biceps and triceps muscle bellies. Preoperative marking is particularly important because the absence of humeral condyles makes it easy to lose landmarks of the arm once the patient is positioned on the operating room table. The procedure is performed with the patient under general anesthesia *without* long-acting muscle relaxants to allow for intraoperative nerve stimulation. The procedure is most easily performed with the patient supine on an arm table, with a position change to prone for the posterior nerve transfers. Although hyperextension of the shoulder can expose the posterior arm, a position change makes the RN dissection much easier to perform. Theoretically, a lateral decubitus position can be used to avoid the position change, but then the tissues are not stabilized during dissection as they are against a firm operating room table.

The anterior incision is made along the previously marked raphe between the long and the short heads of the biceps brachii muscle (Fig. 1A). Within the subcutaneous fat layer, thin skin flaps are elevated, leaving a layer of fat on both the skin flaps and on the deep fascia. We have moved away from hydrodissection with dilute epinephrine solutions because they are unnecessary, can prevent the stimulation of small motor nerves, and prevent the evaluation of tissue vascularity at the end of the procedure. A proximally based adipofascial flap is created approximately 6 cm wide, centered on the raphe, and mobilized proximally

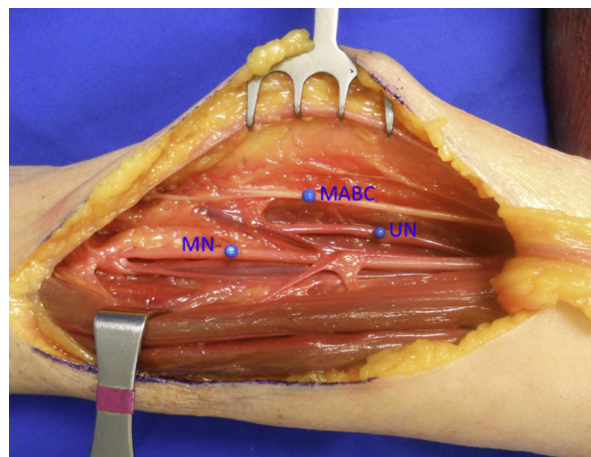


FIGURE 4: Left arm viewed from the head with the medial head of the biceps retracted laterally shows exposure of the MN, UN, and MABC.

until the tendinous aspect of the biceps long head can be seen (Fig. 1B). Identification of the raphe between the muscle heads is greatly facilitated by elevation of this adipofascial flap. Blunt digital dissection between the two heads of the biceps reveals the musculocutaneous nerve (MCN; Fig. 2). This nerve gives off two or more proximal motor branches, one to each head of the biceps muscle, and then continues before branching into the motor branch to the brachialis (MCN-Br) and the lateral antebrachial cutaneous nerve. We have consistently observed this branching to occur a short distance proximal to a crossing vascular arcade, which can be a helpful intraoperative landmark to identify small motor nerve branches (Fig. 3). The motor entry

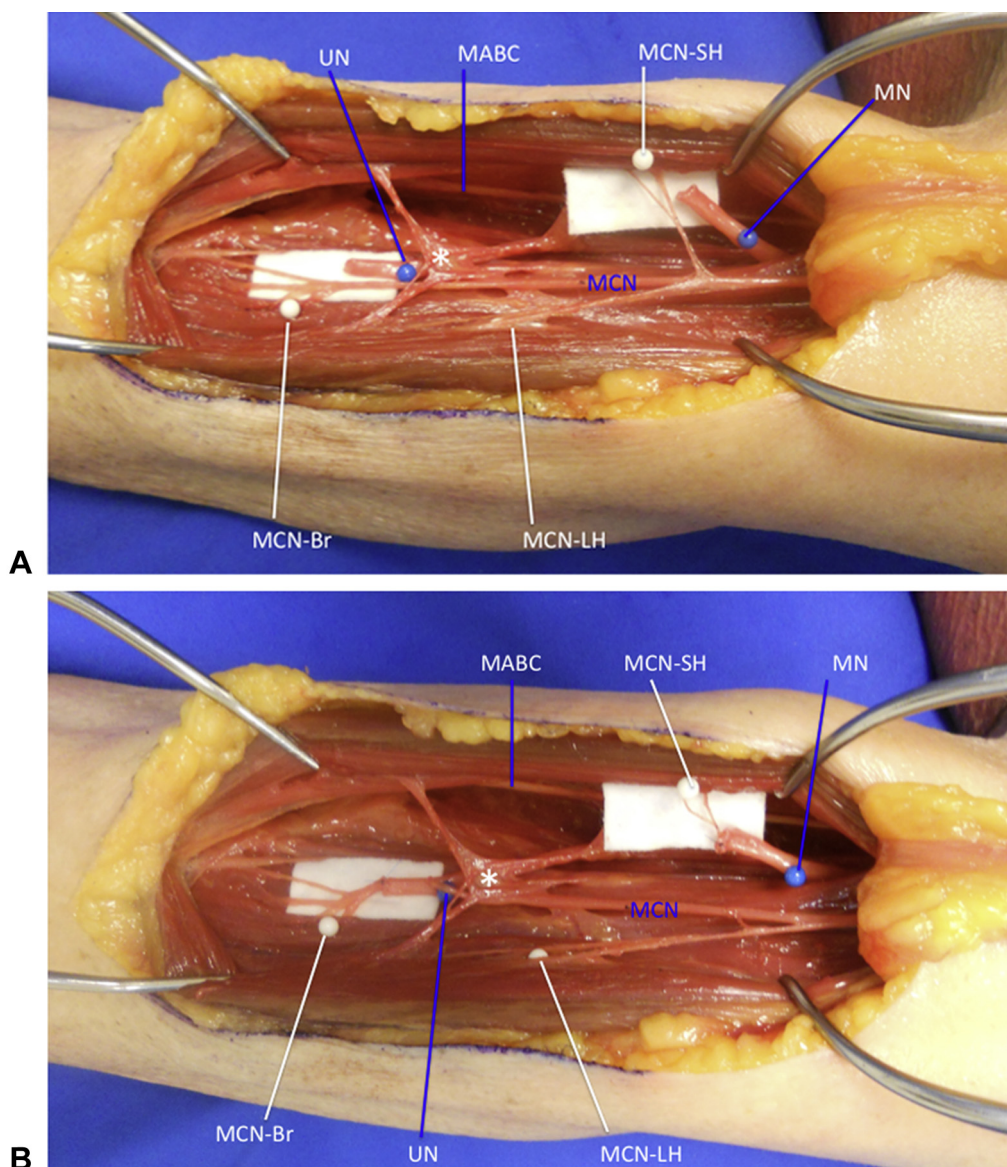


FIGURE 5: Left arm viewed from the head. **A** MN and UN are divided and transposed beneath the medial head of the biceps to their sites of coaptation. **B** Nerve coaptations are completed. Note the branching of the distal MCN just proximal to the crossing of the consistently observed vascular arcade (*). MCH-LH, motor branch to the long head of the biceps; MCN-SH, motor branches to the short head of the biceps.

points into the biceps are usually found at the junction between the proximal and the middle thirds of the muscle, and the motor entry point into the brachialis is found at the junction of the middle and the distal thirds of the brachialis muscle.

Once the MCN motor entry points have been identified, attention turns to identification of the donor brachial nerves. Although both the MN and the UN can be identified and mobilized from within the interspace between the biceps muscle bellies, the dissection is made substantially more easy by transposing the short head of the biceps laterally and working between the muscle belly of the short head

and the intermuscular septum (IMS) on the medial aspect of the arm (Fig. 4). The medial antebrachial cutaneous nerve (MABC) is usually the first nerve encountered in this space, and it should not be mistaken for the MN or UN. It is smaller in caliber and slightly more superficial than either the MN or the UN. The MN is found adjacent to the brachial artery and anterior to the IMS. The MN end neuroma is excised and the residual nerve is trimmed back until healthy fascicles are observed. We have not found it necessary to excise the distal neuroma in its entirety if doing so requires a significant amount of additional dissection. The remaining nerve is carefully transposed deep to

the short head of the biceps into the space between the biceps muscle bellies. The native musculocutaneous motor branch to the short head is divided approximately 1 cm from the muscle belly in order to reduce the technical difficulty of the coaptation while minimizing the time to reinnervation. The proximal aspect of the divided motor nerve is shortened further to move it away from the nerve coaptation site to prevent it from somehow contributing to reinnervation, which we have observed in 1 patient. To ensure that the MN serves as the sole source of innervation to the short head, it is critical that all motor entry points be identified, divided, and included in the coaptation with the MN. Stimulation of the proximal MCN can confirm that all native innervation has been interrupted. The mobilized MN segment is then coapted to the motor nerve entry point using 6-0 or 7-0 polypropylene suture under loupe magnification (Fig. 5B). To protect the coaptation from undue tension, an additional suture is used to secure the MN epineurium to the neighboring epimysium. Alternatively, fibrin glue can be used to reinforce the coaptation.

If there is sufficient residual limb length to allow for reinnervation of the brachialis muscle, the MCN-Br is located by tracing the MCN distally from its biceps branches. To assist with localization of the MCN-Br, the lateral antebrachial cutaneous nerve can be identified distally and traced proximally to the MCN-Br. Stimulation of the motor nerve branch is used to confirm brachialis contraction. Next, the UN is identified posterior to the MN and IMS. Like the MN, it is mobilized along its length, the distal neuroma is resected, and the proximal segment is transposed beneath the short head into the interspace between the biceps muscle bellies. The UN is coapted to the MCN-Br in an analogous fashion to that used for the MN (Fig. 5A, B).

Prior to closure of the anterior incision, the previously elevated adipofascial flap is placed between the long and the short heads of the biceps to insulate and spatially differentiate the future myoelectric signals (Fig. 6). The subcutaneous tissues are closed in standard fashion, and the skin is closed with staples or sutures. If the patient is to remain as an inpatient, a closed-suction drain is used for 24 hours. Alternatively, Ace wrap compression has been used successfully to avoid seroma formation with outpatient procedures.

Future signal acquisition depends on the biceps and/or brachialis being relatively superficial and separate. Adjuncts to this are resection of a small area of the deltoid, division of the tendinous origin of the long head, and wide separation of the heads of the biceps to



FIGURE 6: Left arm viewed from the head shows the adipofascial flap in place, interposed between the biceps heads to isolate electrical signals.

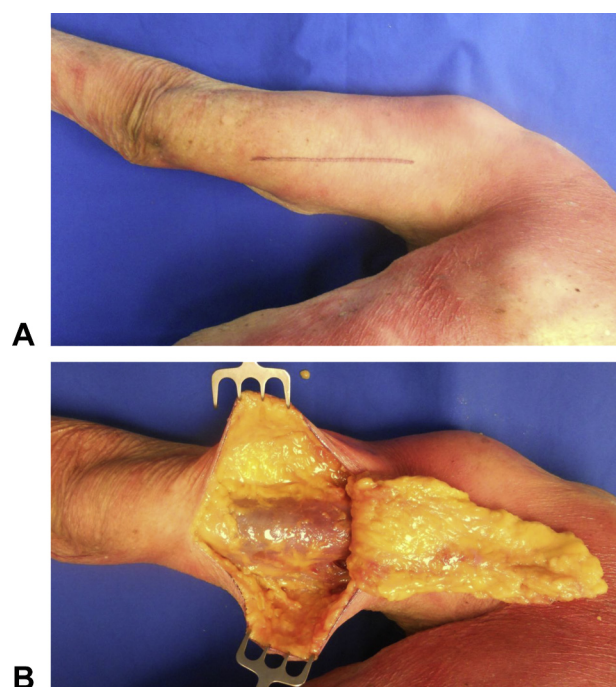


FIGURE 7: Left arm with the patient in the prone position. **A** The incision is centered along the median raphe of the triceps muscle. **B** Elevation of the skin flaps and the proximally based adipofascial flap.

expose the brachialis. The muscle bellies of the biceps should not be mobilized off of the end of the amputation distally because doing so can cause proximal migration of the muscle underneath the deltoid.

The RN transfer is approached posteriorly, through an incision centered along the raphe between the long and the lateral heads of the triceps brachii (Fig. 7A). This dissection proceeds in a similar fashion to the anterior dissection, with elevation of thin skin flaps and a proximally based adipofascial flap centered along the raphe (Fig. 7B). The space between the long

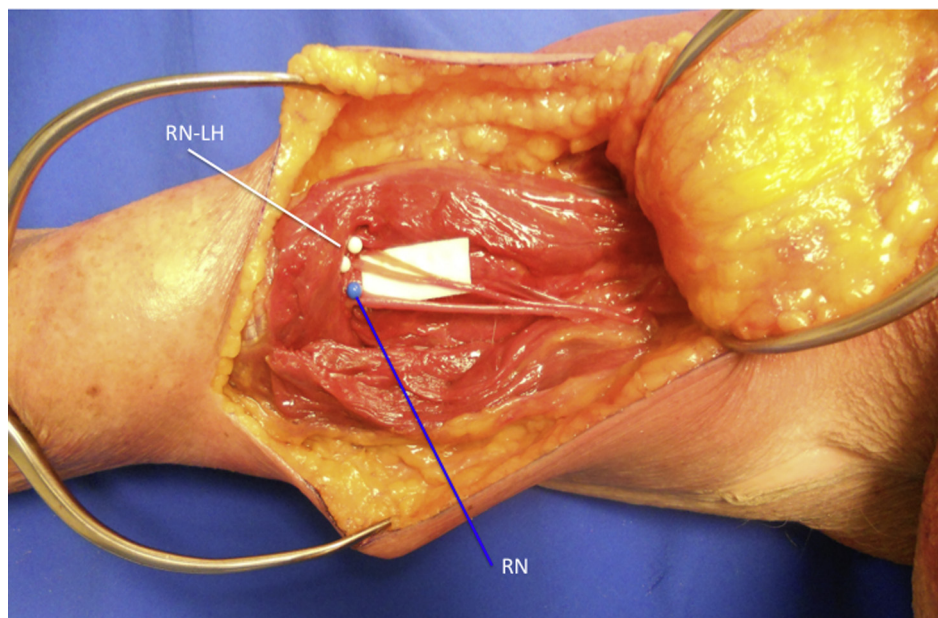


FIGURE 8: Left arm, posterior dissection, viewed from the feet, with medial retraction of the triceps long head revealing the major RN trunk and associated motor branches to the lateral head of the triceps (RN-LH).

and the lateral heads of the triceps is best developed cephalad, near the inferior margin of the deltoid muscle. Medial retraction of the long head typically reveals the major trunk of the RN, with 1 or 2 small motor branches that enter the lateral head between its midpoint and its lower third (Fig. 8). The motor branch to the long head arises very proximal and is not usually encountered in the dissection.⁹ Once the RN is identified, it is stimulated to confirm lack of distal motor activity. The end neuroma is excised and the nerve is trimmed back to healthy-appearing fascicles. The distal RN is then coapted to the lateral head motor branches using the previously described technique (Fig. 9). Because the motor fascicles are interspersed with the sensory fascicles at this level, no attempt is made to further subdivide the RN into sensory or muscle components (unpublished data). In a similar fashion to the anterior transfers, the adipofascial flap is interposed between the long and the lateral heads to isolate the two signals (Fig. 10).

Very long transhumeral amputations and elbow disarticulation patients should be considered for angulation osteotomies of the humerus.^{10,11} Done from the prone position after dissection of the long and lateral heads, a posterior osteotomy plate angled approximately 60° with a 6-cm distal limb is performed with a 2.4 mm dynamic compression plate. If the condyles are present, a shortening of 4 to 5 cm of humeral shaft leaves the condyles in place but adds room for an articulating elbow joint. Angulation osteotomies

aid in rotational control of the prosthesis and prevent the socket from sliding off of the residual limb.

SHOULDER DISARTICULATION LEVEL

Surgical rationale

Targeted muscle reinnervation in the shoulder disarticulation patient is made more challenging by the proximal extent of nerve injury and the greater likelihood of damage to potential muscle targets. Similarly, a compromised soft tissue envelope is the rule rather than the exception. As a consequence, preoperative assessment of remnant muscle function is critical, as is an evaluation of the soft tissue quality on which the shoulder harness will rest. Whereas TMR in the transhumeral patient is straightforward and predictable, TMR at the shoulder disarticulation level requires intraoperative flexibility and comfort with distortion of the regional anatomy. The added level of complexity is evidenced by a recent review of 26 consecutive TMR patients. The same pattern of nerve transfers was used for all 16 transhumeral patients, whereas 7 different nerve transfer combinations were used in the 10 shoulder disarticulation TMR patients included in the study.³

Surgical technique

The presence or absence of a humeral head is confirmed by plain radiographs. Absence of the humeral head will cause the pectoralis major and associated structures to

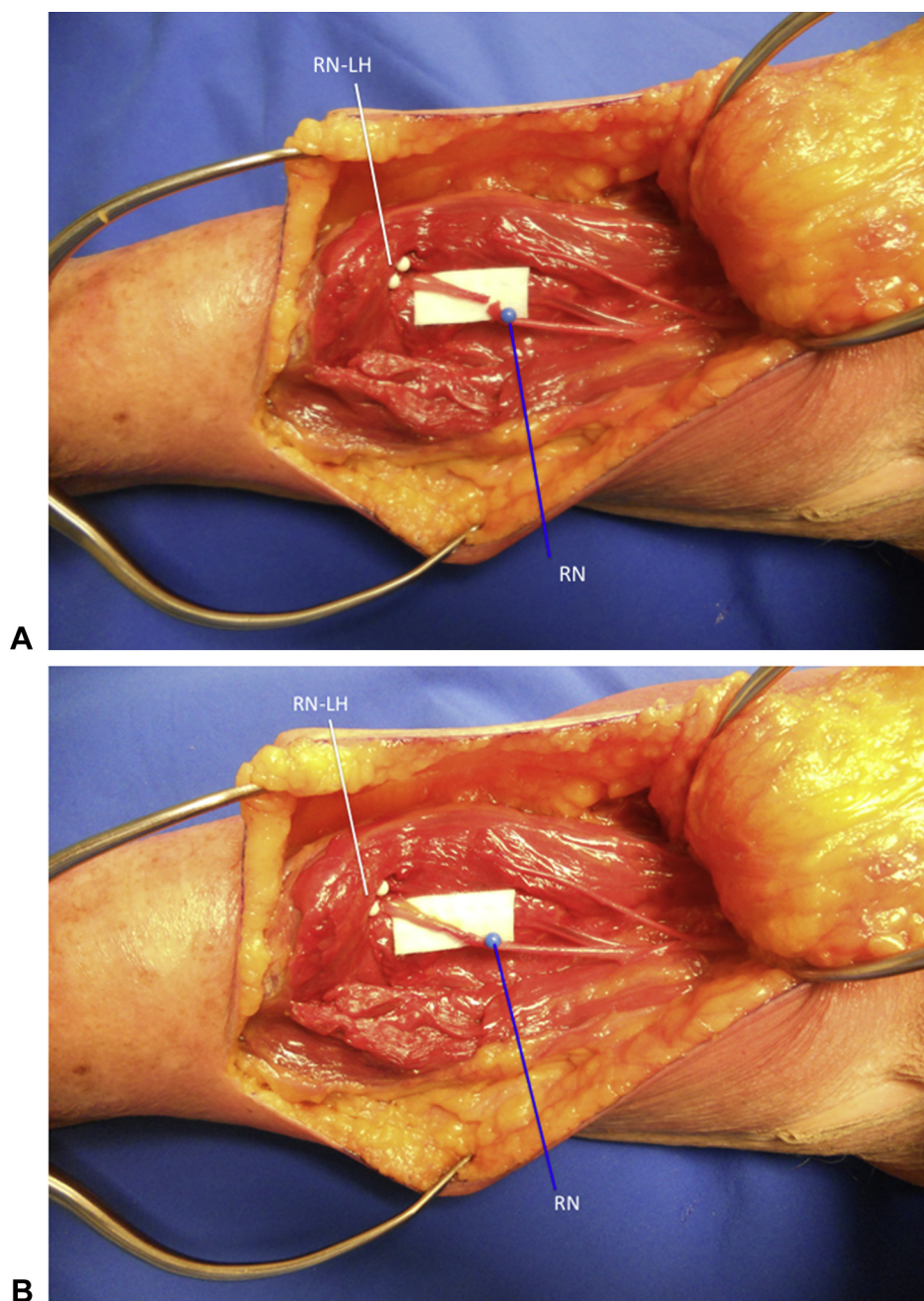


FIGURE 9: Left arm, posterior dissection, viewed from the feet, with the RN transected. **A** Approximation of the distal RN to the motor nerve branches to the long head of the triceps (RN-LH). **B** Completion of nerve coaptation.

be located 4 to 6 cm more medial than expected. Presence of the humeral head can be associated with a remnant of the triceps and persistent innervation by the RN. This should be sought and preserved during the course of the dissection.

The brachial plexus is accessed through a transverse incision placed 2 fingerwidths below the clavicle. A medially based adipofascial flap is elevated, analogous to that used for the transhumeral procedure (Fig. 11). To facilitate signal detection after surgery, the skin overlying the pectoralis muscle is widely

thinned to minimize the distance between the reinnervated muscle and the surface electrodes, and owing to the excellent subdermal plexus, vascularity of the flaps has not been compromised. Dissection proceeds by developing the space between the sternal (SH) and the clavicular (CH) heads of the pectoralis major. This space is often marked by a fat stripe visible between the pectoralis muscle fibers (Fig. 11). At the depths of this space are the thoracoacromial pedicle and the crossing motor nerves to the SH. The thoracoacromial vascular pedicle to the pectoralis

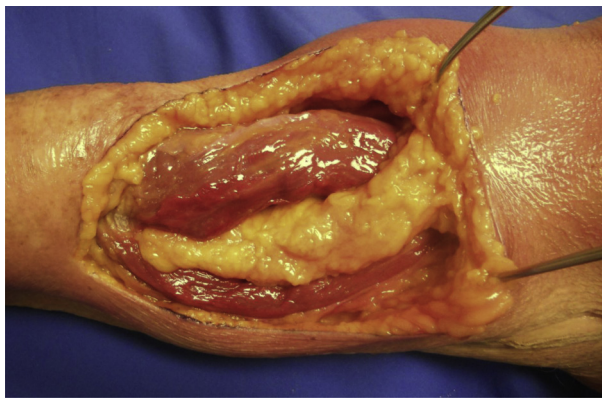


FIGURE 10: Completed posterior dissection of the left arm shows the proximally based adipofascial flap in place, between the heads of the triceps muscles to isolate electrical signals.

should be mobilized and preserved to aid in later free-style splitting of the SH. The superior, middle, and lateral motor branches to the SH are identified. The superior pectoral nerve, from the anterior division of the upper trunk, begins distal to the supra-scapular nerve and pierces the clavipectoral fascia just distal to the clavicle, supplying the lateral CH with 2 to 4 motor branches. The middle pectoral nerve forms from the anterior division of the middle trunk and pierces the medial clavipectoral fascia, supplying the medial CH and upper SH. The inferior nerve, the largest of all three, forms from the lower trunk and courses posterior to the axillary artery before turning sharply upward at the takeoff of the lateral thoracic artery, looping around it to form a plexus of nerves with the deep branch of the middle pectoral nerve.¹²

Whereas their anatomy may help to identify them, the origin of these nerves from the plexus does not matter. Rather, an identification of all motor branches to the pectoralis must be performed so that, prior to nerve transfers, the pectoralis has been completely denervated. Denervation of the pectoralis muscle has no functional consequences in the shoulder disarticulation amputee, but failure to fully denervate the muscle can compromise interpretation of the re-innervated signals. Placement of a self-retaining retractor at this point further opens the space to finally identify the motor branch to the CH that enters the muscle in a vertical direction adjacent to the vascular pedicle. The thoracodorsal and/or long thoracic nerve dissection must wait for the dissection of the brachial plexus—level amputated nerves.

The brachial plexus is identified first by palpation within the fatty tissue found in the space between the SH and the CH. The cords can be identified either

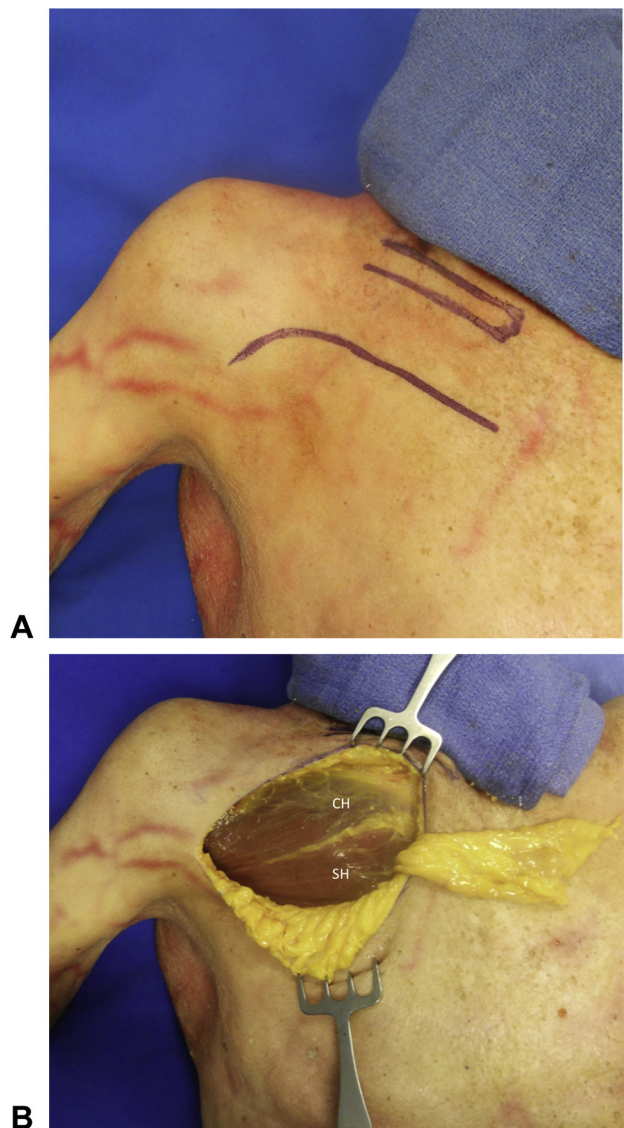


FIGURE 11: Shoulder disarticulation TMR. **A** Incision planned 2 fingerbreadths below the clavicle, along the raphe between the CH and the SH. **B** Following elevation of skin flaps and the medially based adipofascial flap. Note the fat stripe marking the division between the two heads of the pectoralis major.

medial or lateral to the pectoralis minor (Fig. 12). However, it is not uncommon for the plexus to be encased in scar or even within heterotopic ossification. If necessary, the pectoralis minor should be divided for improved access. The brachial artery has not been problematic in these high amputees, perhaps because the vessel may thrombose proximally. In these cases, the relative anatomy of the plexus at the cord or nerve level is distorted, and accurate identification of the individual donor nerves is challenging. Fortunately, the pattern of nerve transfers in the shoulder disarticulation patient is less dependent on accurate identification of the donor nerve and more subject to the

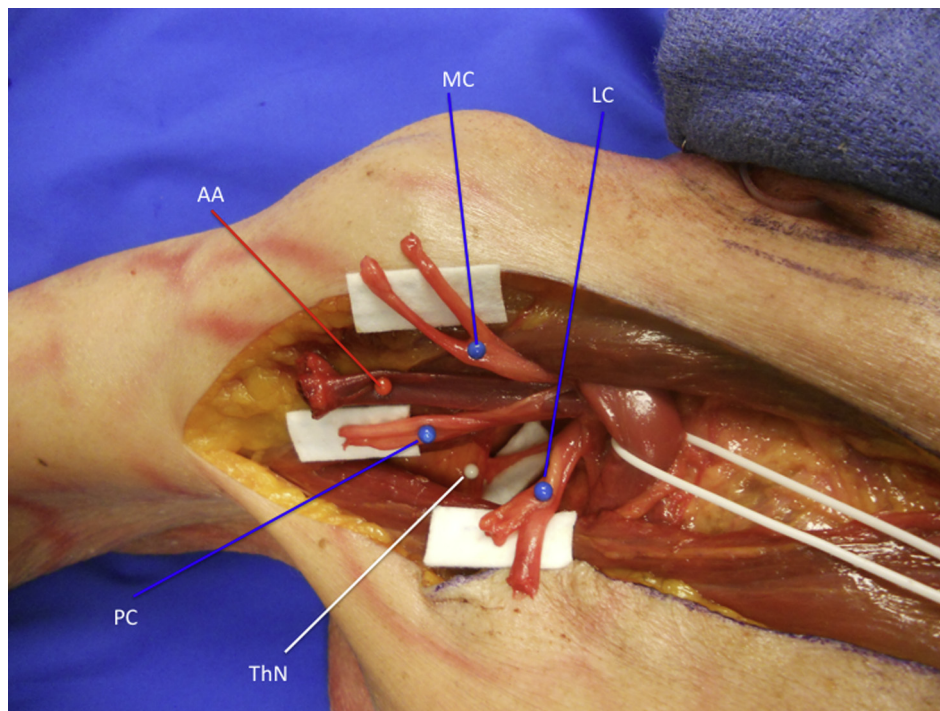


FIGURE 12: The brachial donor nerves are demonstrated as they course beneath the pectoralis minor insertion (white vessel loop). The lateral (LC), medial (MC), and posterior (PC) cords are labeled with blue pins. The thoracodorsal nerve (ThN) is marked with a white pin as it travels beneath the latissimus insertion. The axillary artery (AA) is labeled with a red pin.

spatial relationship between the donor nerves and the recipient muscle targets. In the end, each successful neurotization will produce a myoelectric signal that can be used to govern a prosthetic function regardless of its location. That said, under ideal circumstances, the MCN is paired with the motor branch of the CH, the MN and UN are transferred to motor branches corresponding to split segments of the sternal head, and the RN is coapted to the thoracodorsal nerve (Fig. 13).

Splitting the pectoralis depends on a visual evaluation of how the muscle contracts with stimulation of different motor nerves and the vascular pedicle anatomy. The rationale for this pattern stems from the fact that the MCN provides neural control for a single function, elbow flexion, which is high on the functional hierarchy. It is thus paired with the CH, a muscle target that consistently provides the strongest and most predictable myoelectric signal as a result of its superficial location, thin overlying skin, and the stability of the associated clavicle bone. Prior to definitive closure, the previously elevated adipofascial flap is split and interposed as two separate flaps between the CH and the split SH segments. Because this flap can be thick, it is sometimes reduced in size and used as free fat grafts between muscle segments rather than vascularized tissue. Quilting sutures are placed and the skin is closed in layered fashion over

suction drains to minimize seroma formation. The suction drains are left in place for 2 to 5 days.

In the absence of usable native muscle targets, the pectoralis minor and serratus anterior can be used as alternative transfer recipients; however, their relative depth can make surface recording challenging. Alternatively, free tissue transfer can be utilized to bring recipient muscles to the amputation site. In this case, it is preferable to utilize a flap that transfers multiple independently innervated muscle segments (ie, serratus anterior). In 1 case of a forequarter amputation, a volar forearm myocutaneous flap was used successfully for both soft tissue cover and muscle targets.

POSTOPERATIVE CARE

By convention, patients are usually observed overnight and discharged home the following day, although if pain were to be well controlled, there is no reason that TMR could not be performed in the outpatient setting. Bulky compressive dressings are used to minimize postoperative swelling, but the residual limb is not otherwise immobilized. Patients can resume wearing their original prosthesis once wound healing is adequate and swelling has subsided enough to allow for a proper fit, generally 4 to 6 weeks after surgery.¹³ All patients should be informed that they might

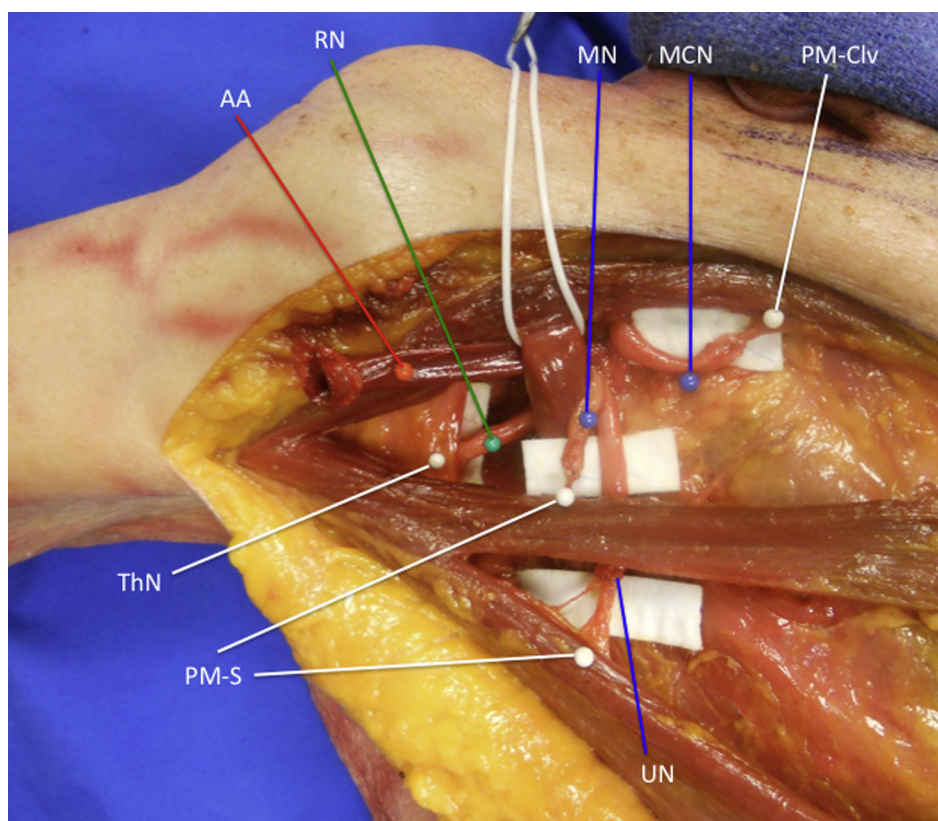


FIGURE 13: Nerve transfers at the shoulder disarticulation level. The MCN is coapted to the motor branch to the clavicular head of the pectoralis major (PM-Clv), while the MN and UN are transferred to split segments of the sternal head (PM-S). The RN is transferred to the thoracodorsal nerve (ThN). AA, axillary artery.

experience altered sensation in the skin overlying the reinnervated muscles. With regard to phantom pain, we have found that patients who report phantom pain prior to the procedure generally experience an exacerbation of their phantom symptoms that lasts 4 to 6 weeks but typically returns to baseline. None of our patients has developed *de novo* phantom pain following this procedure. As with all nerve transfers, reinnervation time varies based on the distance from the nerve coaptation to the neuromuscular junction, but successful reinnervation generally occurs within 3 to 6 months. Use of the latissimus muscle as a target requires the longest reinnervation distance and time. Myoelectric testing and prosthetic fitting is usually initiated no sooner than 6 months after TMR.

CLINICAL CASE

We present the case of a 43-year-old man with a long transhumeral amputation as a result of a train accident. He was originally treated at an outside facility and fitted with a conventional prosthesis. He was subsequently referred to our facility for improved prosthetic control. At presentation, he was found to have strong biceps and triceps function. He underwent a standard transhumeral

TMR procedure with a simultaneous humeral angulation osteotomy, using the techniques outlined previously (Fig. 14). He recovered uneventfully and has been fitted with a TMR-controlled device (Fig. 15).

PEARLS AND PITFALLS

Although the operation can be performed without a position change, we find that this significantly reduces the difficulty of the operation and does not significantly prolong operative time for transhumeral amputations.

One should be certain that all motor branches to the target muscles are identified. It is critical to completely denervate the target muscles before nerve transfer to encourage reinnervation and minimize signal cross-talk.

Cross-talk is lessened by placement of the adipofascial flaps. The only patient to have reinnervation of a single muscle segment from multiple nerves did not have any local fat for placement into the space owing to a significant burn injury.

Limiting the amount of tissue between the skin surface and the underlying muscle improves signal detection. Skin flaps are best thinned directly.

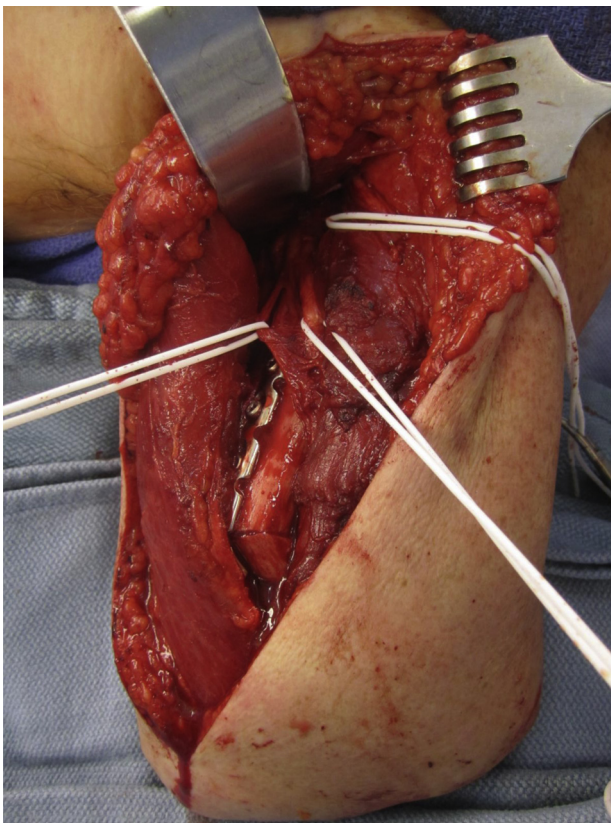


FIGURE 14: Left shoulder, posterior approach, shows the angulation osteotomy with a 2.4 mm dynamic compression plate. Vessel loops show the RN and the motor branches to the triceps muscle heads.

In transhumeral TMR, there is nearly always excess donor nerve length, which allows for aggressive trimming in order to ensure that healthy nerve fascicles are present at the nerve coaptation site.

In shoulder disarticulation patients, there is less room for generous trimming of donor nerves; however, the maximum amount of nerve resection should be performed to reach healthy fascicular architecture without placing nerve coaptations under tension.

Adjuncts such as nerve wraps and glues have not seemed to be necessary. Nerve grafts to achieve a tension-free repair have not been performed by our group. Rather, mobilization of the muscle toward the nerve using muscle flap techniques has been the preferred option.

The first nerve that is found while looking for the median nerve for transhumeral TMR is the MABC. With no forearm present, stimulation will not be able to separate the MABC from the MN. The MN is larger and adjacent to the brachial artery.

Preservation of a small, innervated remnant of the triceps can aid in prosthetic control of shoulder disarticulation patients. However, it makes the subsequent



FIGURE 15: Postoperative photograph demonstrates functional use of the right upper extremity myoelectric prosthesis.

treatment of the remainder of the RN more awkward because the nerve may then be difficult to mobilize to reach a suitable target in this situation. Intraneural dissection to split off the triceps motor branch from the main nerve will be necessary.

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