SCIENTIFIC ARTICLE

Neurotization to Innervate the Deltoid and Biceps: 3 Cases

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Purpose To describe our experience using direct muscle neurotization as a treatment adjunct during delayed surgical reconstruction for traumatic denervation injuries.

Methods Three patients who had direct muscle neurotization were chosen from a consecutive series of patients undergoing reconstruction for brachial plexus injuries. The cases are presented in detail, including long-term clinical follow-up at 2, 5, and 10 years with accompanying postoperative electrodiagnostic studies. Postoperative motor strength using British Medical Research Council grading and active range of motion were retrospectively extracted from the clinical charts.

Results Direct muscle neurotization was performed into the deltoid in 2 cases and into the biceps in 1 case after delays of up to 10 months from injury. Two patients had recovery of M4 strength, and the other patient had recovery of M3 strength. All 3 patients had evidence on electrodiagnostic studies of at least partial muscle reinnervation after neurotization.

Conclusions Direct muscle neurotization has shown promising results in numerous basic science investigations and a limited number of clinical cases. The current series provides additional clinical and electrodiagnostic evidence that direct muscle neurotization can successfully provide reinnervation, even after lengthy delays from injury to surgical treatment.

Clinical relevance Microsurgeons should consider direct muscle neurotization as a viable adjunct treatment and part of a comprehensive reconstructive plan, especially for injuries associated with avulsion of the distal nerve stump from its insertion into the muscle. *(J Hand Surg 2013;38A:237–240.*

Key words: Brachial plexus, direct muscle neurotization, nerve-to-muscle transfer.

Chronic peripheral nerve injuries with avulsion of the nerve from the muscle present a challenge to the microvascular surgeon. The pattern of injury and posttraumatic scarring can preclude preferred techniques such as direct nerve repair or nerve grafting. In these situations, direct muscle neurotization (DMN) has been sporadically used to attempt reinnervation of denervated muscle. The procedure, originally described in the early 20th century by multiple investigators,[1–4] involves sectioning the healthy stump of proximal nerve, dividing its fascicles, and inserting the fascicles into the muscle belly.[5] Basic science models[6–13] have provided the neuroregenerative framework for the procedure, but clinical results[14–18] have had conflicting results, and typically, DMN is offered as a reconstructive option only as a last resort for patients with denervated muscle.

Although DMN was first investigated in the acute reconstructive setting,[8] ongoing research has shown its effectiveness in delayed[16,17] reconstructive surgery. Previous animal experiment has suggested that DMN might play a particularly important role as an alternative to neurorrhaphy in the setting of prolonged denerva-

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tion.[13] In the current series, we present our clinical and electrodiagnostic results when using DMN as a targeted treatment adjunct in 3 patients having surgical reconstruction 4, 6, and 10 months after denervation injuries.

MATERIALS AND METHODS

We retrospectively reviewed the data of 64 consecutive brachial plexus surgeries performed over a 12-year period, after approval from our institutional review board. All brachial plexus reconstructive surgeries were performed by a single surgeon and evaluated at several postoperative time points. Data were collected prospectively using a web-based, password-protected clinical research data entry application. Standardized data collection forms were used for each visit (eg, patient demographics, injury details, surgical details, motor and sensory outcome, and electrodiagnostic studies). In compliance with patient privacy regulations, security features in the database enabled the de-identification of patient health information.

Three patients were identified as having had DMN for an otherwise unreconstructable nerve injury. Preoperative evaluations, preoperative plans, intraoperative findings, and postoperative course at the latest follow-up visit were reviewed. The outpatient medical charts were reviewed for neurologic examinations, including sensibility and muscle strength as graded by the British Medical Research Council,[19] follow-up electrodiagnostic studies, and notable postoperative events and/or complications. All neurologic examinations were performed by the senior author (S.W.W.), a fellowship-trained hand surgeon with extensive experience in microsurgical reconstruction. The patients in cases 1 and 2 were specifically contacted to come for a follow-up examination for research purposes.

In general, we use DMN when neurorrhaphy and nerve transfer are not possible due to avulsion of the injured nerve from muscle. A longitudinal slit is made in the fascia of the target muscle. The proximal stump of the nerve is embedded into the muscle belly. No effort is made to fan out the fascicles of the nerve graft. An 8-0 or 9-0 nylon suture is used to close the epimysium and secure the nerve. Gentle range of motion of the extremity is checked to ensure that the embedded nerve is not under tension.

RESULTS

Case 1

An otherwise-healthy, 17-year-old, right-handed teenager was involved in a head-to-head snowmobile collision and hospitalized at another institution. He sustained multiple organ system trauma, including a right pneumothorax (treated with a right chest tube), closed right scapula fracture, extra-articular distal radius and distal ulna fractures, and intracranial and spinal cord trauma. He was noted to have a flail and completely insensate right upper extremity on admission, but he developed return of sensation in his hand and some early mobility before discharge. He presented to our institution for evaluation of his peripheral nerve injury after treatment had been deferred at the other hospital.

Initial examination revealed mild pupillary asymmetry with right myosis and slight ptosis. Gross motor testing showed absent (M0) motor function of the deltoid, supraspinatus, infraspinatus, latissimus dorsi, pectoralis major, biceps, brachioradialis, triceps, and extensor carpi radialis longus. Sensory examination revealed markedly diminished sensation to light touch and 2-point discrimination in the C5-C6 distribution. Electrodiagnostic studies performed 3 months after the injury demonstrated a mixed cervical root and brachial plexus injury involving all root levels and trunks. Specifically, there was denervation of the deltoid in the form of 2+ positive sharp waves and fibrillation potentials with no motor units.

The patient had surgical exploration of the brachial plexus 4 months after injury. The spinal accessory nerve was transferred to the suprascapular nerve, and an Oberlin procedure[20] was performed, as planned. The preoperative plan for the C5 root–to–axillary nerve transfer was changed after dissection of the distal portions of the plexus revealed the axillary nerve to be completely avulsed from the deltoid muscle. Two cable grafts from the C5 root were embedded into the anterior deltoid using 9-0 nylon sutures. An 8-0 nylon suture was used to close the epimysium and to secure the nerves in place.

Physical examination 9 months after surgery revealed M0 strength of the deltoid. Active shoulder forward flexion was approximately 20°. Examination 5 years after surgery revealed active forward flexion of more than 90° and active abduction to 80°, with apparent function of all heads of the deltoid. Deltoid strength was M3. Electrodiagnostic studies demonstrated partial re-innervation of the deltoid, with moderate motor unit recruitment, fibrillation potentials, and positive sharp waves.

Case 2

An otherwise-healthy, 38-year-old construction worker was struck on the head and right shoulder by a 1,360-kg metal construction beam. The patient suffered a severe right brachial plexus injury and a closed right proximal humerus fracture. The humeral fracture healed uneventfully after intramedullary nailing, and the patient was referred to our institution for management of his brachial plexus injury.

Three months after injury, there was an absence of motor function (M0) in the deltoid, triceps, biceps, brachioradialis, extensor carpi radialis longus, extensor carpi radialis brevis, extensor pollicis longus, extensor digitorum communis, pronator teres, flexor carpi radialis, median flexor digitorum profundus, and flexor pollicis longus. Sensibility to light touch was absent in C5, C6, and C7 but slightly preserved in C8 and T1. Subclavian artery pulse was palpable, but brachial, radial, and ulnar pulses were not appreciable on examination by a vascular surgeon. Electrodiagnostic studies performed 4 months after the injury demonstrated total denervation of the biceps in the form of 4+ positive sharp waves and 3+ fibrillation potentials, with no motor units. Sensory conduction in the lateral antebrachial cutaneous nerve was absent.

The patient had reconstruction 6 months after injury. Intraoperative findings revealed complete disruption of the proximal biceps muscle belly and the musculocutaneous nerve at its most distal insertion site into the biceps, without a visible distal nerve segment, precluding the planned Oberlin procedure.[20] A 15-cm portion of sural nerve was grafted to a large branch of the intact medial pectoral nerve, and this graft stump was embedded into the biceps muscle belly in its midportion.

Biceps twitches were present on clinical examination 10 months after surgery. Elbow flexion against gravity with detectable active biceps contraction and supination was present 13 months after surgery. At 11 years after surgery, the patient had M4 strength in the biceps, with full active elbow flexion. Electrodiagnostic studies showed full recruitment of the biceps, without further denervation. There was no abnormal spontaneous electrophysiological activity recorded.

Case 3

An otherwise-healthy, 29-year-old, right handed woman injured her right shoulder in a motor vehicle collision. She was treated at another institution with closed reduction and percutaneous pinning of her proximal humerus fracture within 2 days of the accident, but she subsequently developed a nonunion. She was referred to our center 10 months after the injury for persistent shoulder pain, weakness, and dysfunction.

Examination showed the anterior, middle, and posterior portions of the right deltoid to be markedly atrophic and nonfunctional. The patient was able to actively forward flex to 20° with pain and actively rotate 20° internally and externally with pain, but she was not able to actively abduct her shoulder.

Radiographic images demonstrated a nonunion at the surgical neck of the humerus. Electrodiagnostic studies performed 10 months after the injury demonstrated a complete axillary neuropathy involving the branch to the anterior and middle deltoids and an incomplete axillary neuropathy involving the branch to the posterior deltoid (there were 2+ positive sharp waves and fibrillation potentials).

Following open reduction and internal fixation and bone grafting of the surgical neck nonunion, the patient was repositioned, and the radial nerve branches to the triceps were dissected. The preoperative plan was to transfer a radial nerve branch from the long head of the triceps to the distal stump of the axillary nerve to the anterior and middle deltoid. However, upon proximal dissection to identify the branches of the axillary nerve, the branch of the axillary nerve to the anterior and middle deltoid was avulsed from the hub of the axillary nerve in the quadrangular space. The distal nerve stump to the anterior and middle deltoid was not identifiable. In addition, the branch of the axillary nerve to the posterior deltoid and a small posterior axillary cutaneous nerve were encased in dense scar.

Based on these findings, the surgical plan was changed to use the posterior axillary cutaneous nerve as a graft to span between the fascicles of the long head triceps branch of the radial nerve to the anterior and middle deltoid. The axillary nerve branch to the posterior deltoid and the posterior axillary cutaneous nerve were neurolysed. Direct stimulation of the branch of the axillary nerve to the posterior head of the deltoid resulted in a vigorous contraction. The posterior cutaneous nerve was divided, reversed, and sewn to the distal end of the long head triceps branch. A longitudinal slit was made in the fascia of the anteromedial deltoid, and the distal stump of the nerve graft was embedded into the muscle.

Five months after surgery, the patient's shoulder abduction increased to 90°, and she was able to perform most activities of daily living. By 2 years, she was able to actively abduct to 110° with M4 strength and to elevate the arm overhead while lying supine.

Electrodiagnostic studies performed 8 months after surgery demonstrated polyphasic motor unit potentials with reduced motor unit recruitment, indicating regenerating motor units in the anterior and middle portions of the deltoid. In addition, the absence of positive sharp waves and fibrillation potentials in the posterior deltoid suggested that the active denervation present in the preoperative study was partially resolved.

DISCUSSION

Traumatic nerve injuries continue to bear a guarded prognosis. Although primary nerve repair is desirable, the complex injury pattern often precludes immediate surgical intervention. In specific injuries, avulsion of the nerve at its insertion point at the muscle precludes preferred techniques such as nerve repairs, transfers, and grafting. Surgeons must be prepared to use alternative techniques in these challenging situations.

Direct muscle neurotization has shown promising results in experimental animal models[6–13,15] and in a limited number of human cases.[6,15–18] The principle of DMN is based on 4 physiologic phenomena[21]: (1) stimulation of axonal growth by neurotrophic factors, (2) increased sensitization of denervated muscle for motor axons, (3) formation of new motor end plates, and (4) reinnervation of 2–3 muscle fibers by a single motor axon (the "adoption" or "splitting" phenomena). Both DMN and neurorrhaphy can independently increase the number of muscle fibers,[9,12] but these 2 mechanisms of neurotization may work best when complementing each other.[10] Although DMN is not as efficient as nerve grafting in the setting of acute reconstruction,[12,22] animal models suggest that DMN may have a specific role both as an adjunct to neurorrhaphy in the acute setting and as a primary method of muscle renervation in the chronic setting.[10,13] Our series of 3 patients provides promising clinical support that DMN can provide functional recovery in humans and corroborates the reports of other investigators.[14–18] The clinical results in our patients are substantiated by improvement on postoperative electrodiagnostic studies. In case 3, the branch of the axillary nerve to the posterior deltoid was intact, and its recovery after neurolysis may have contributed substantially to the improvement in shoulder abduction at final follow-up. However, postoperative electrodiagnostic studies revealed specific improvement in the biceps (in case 2) and the anterior and middle heads of the deltoid (in case 3), suggesting that DMN was successful.

We recommend that a comprehensive approach should be taken when treating nerve lesions associated with complex injuries. Direct muscle neurotization should not necessarily be viewed as a salvage treatment but as a potent adjunctive treatment and part of a comprehensive reconstructive plan, especially for injuries associated with avulsion of the nerve from the muscle. Although some reconstructive surgeons may prefer tendon or muscle transfers if neurorrhaphy or nerve transfer is not possible, DMN may be a useful option to stimulate muscle recovery after prolonged de-innervation that does not preclude subsequent use of these procedures. Our case series is an example of how DMN can be used in concert with nerve transfers and nerve grafts, even with delays from injury to reconstruction of up to 10 months.

REFERENCES

1. Erlacher P. Ueber die motorischen Nervenendigungen. Histologische und experimentelle Beitraege zu den Operationen an den peripheren Nerven. *Zeitschrift fuer orthopaedische Chirurgie.* 1914;34:561.
2. Gersuny R. Eine Operation bei motorischen Laehmungen. *Weiner klinische Worhenschrift.* 1906;19:263.
3. Hacker V. Erfolgreich operativ behandelte Cucullarislaehmung. Verein der Aerzte in Steiermark. *Wien Klin Wochenschr.* 1908;21:1314.
4. Heineke D. Die directs Einflanzung des Nerfs in den Muskel. *Zentralb Chir.* 1914;41:465.
5. Meals RA, Nelissen RG. The origin and meaning of "neurotization." *J Hand Surg Am.* 1995;20(1):144–146.
6. Brunelli G. Direct neurotization of severely damaged muscles. *J Hand Surg Am.* 1982;7(6):572–579.
7. Payne SH Jr, Brushart TM. Neurotization of the rat soleus muscle: a quantitative analysis of reinnervation. *J Hand Surg Am.* 1997;22(4): 640–643.
8. Keilhoff G, Fansa H. Successful intramuscular neurotization is dependent on the denervation period. A histomorphological study of the gracilis muscle in rats. *Muscle Nerve.* 2005;31(2):221–228.
9. Noordin S, Ahmed M, Rehman R, et al. Neuronal regeneration in denervated muscle following sensory and muscular neurotization. *Acta Orthop.* 2008;79(1):126–133.
10. Papalia I, Lacroix C, Brunelli F, d'Alcontres FS. Direct muscle neurotization after end-to-side neurorrhaphy. *J Reconstr Microsurg.* 2001;17(4):237–246.
11. Sakellarides HT, Sorbie C, James L. Reinnervation of denervated muscles by nerve transplantation. *Clin Orthop Relat Res.* 1972;83: 195–201.
12. Sorbie C, Porter TL. Reinnervation of paralysed muscles by direct motor nerve implantation. An experimental study in the dog. *J Bone Joint Surg Br.* 1969;51(1):156–164.
13. Swanson AN, Wolfe SW, Khazzam M, et al. Comparison of neurotization versus nerve repair in an animal model of chronically denervated muscle. *J Hand Surg Am.* 2008;33(7):1093–1099.
14. Brunelli GA, Brunelli GR. Direct muscle neurotization. *J Reconstr Microsurg.* 1993;9(2):81–90; discussion 89–90.
15. Mackinnon SE, McLean JA, Hunter GA. Direct muscle neurotization recovers gastrocnemius muscle function. *J Reconstr Microsurg.* 1993;9(2):77–80.
16. Becker M, Lassner F, Fansa H, et al. Refinements in nerve to muscle neurotization. *Muscle Nerve.* 2002;26(2):362–366.
17. Sinis N, Boettcher M, Werdin F, et al. Restoration of shoulder abduction function by direct muscular neurotization with the phrenic nerve fascicles and nerve grafts: a case report. *Microsurgery.* 2009; 29(7):552–555.
18. Terzis JK, Karypidis D. Outcomes of direct muscle neurotisation in adult facial paralysis. *J Plast Reconstr Aesthet Surg.* 2011;64(2): 174–184.
19. Medical Research Council. *Aids to the Investigation of Peripheral Nerve Injuries*. London: Her Majesty's Stationery, 1943.
20. Oberlin C, Beal D, Leechavengvongs S, et al. Nerve transfer to biceps muscle using a part of ulnar nerve for C5-C6 avulsion of the brachial plexus: anatomical study and report of four cases. *J Hand Surg Am.* 1994;19(2):232–237.
21. Gutmann E. Effect of delay of innervation on recovery of muscle after nerve lesions. *J Neurophysiol.* 1948;11(4):279–294.
22. McNamara MJ, Garrett WE Jr, Seaber AV, et al. Neurorrhaphy, nerve grafting, and neurotization: a functional comparison of nerve reconstruction techniques. *J Hand Surg Am.* 1987;12(3):354–360.