Restoration of hand function and so called “breathing arm” after intraspinal repair of C5–T1 brachial plexus avulsion injury

Case report

**THOMAS CARLSTEDT, M.D., D.M., F.R.C.S., PRAVEEN ANAND, M.D., F.R.C.P.,
MIN HTUT, M.R.C.P., PETER MISRA, M.D., F.R.C.P., AND MIKAEL SVENSSON, M.D., D.M.**

*The Periphery Nerve Injury Unit, The Royal National Orthopaedic Hospital, Stanmore;
Peripheral Neuropathy Unit, Imperial College, Hammersmith Hospital, London, United Kingdom;
and Department of Neurosurgery, Karolinska Hospital, Stockholm, Sweden*

This 9-year-old boy sustained a complete right-sided C5–T1 brachial plexus avulsion injury in a motorcycle accident. He underwent surgery 4 weeks after the accident. The motor-related nerve roots in all parts of the avulsed brachial plexus were reconnected to the spinal cord by reimplantation of peripheral nerve grafts. Recovery in the proximal part of the arm started 8 to 10 months later. Motor function was restored throughout the arm and also in the intrinsic muscles of the hand by 2 years postoperatively. The initial severe excruciating pain, typical after nerve root avulsions, disappeared completely with motor recovery. The authors observed good recruitment of regenerated motor units in all parts of the arm, but there were cocontractions. Transcranial magnetic stimulation produced response in all muscles, with prolonged latency and smaller amplitude compared with the intact side. There was inspiration-evoked muscle activity in proximal arm muscles—that is, the so-called “breathing arm” phenomenon. The issues of nerve regeneration after intraspinal reimplantation in a young individual, as well as plasticity and associated pain, are discussed.

To the best of the authors’ knowledge, the present case demonstrates, for the first time, that spinal cord surgery can restore hand function after a complete brachial plexus avulsion injury.

**KEY WORDS • brachial plexus injury • avulsion • intraspinal repair •
hand function • pediatric neurosurgery**

Spinal nerve root avulsions occur mostly from traction-related traumatic injury to the brachial plexus; they represent a “longitudinal” spinal cord injury.⁹ In this severe nerve injury, the patient experienced arm and hand paralysis and no sensation. In most cases there is a typical severe, excruciating pain due to deafferentation of the spinal cord.²¹ Pain and loss of function dominate the patient’s life.¹²

The objectives of treatment are alleviation of pain and restoration of some useful function. Current surgical treatments are palliative. Through nerve transfers (“neurotizations”) nerves outside the brachial plexus are rerouted and connected to nerves within it.¹⁹ Neural circuits not involved in the avulsion injury can, after nerve transfers, mediate limited movements and, to some degree, sensations referred from the reinnervated arm. After a complete brachial plexus avulsion injury, a limited recovery of

function in the proximal part of the arm is attainable after this surgery. Recovery of hand function is not possible.

A direct, curative surgical technique for nerve root avulsions has been described and applied clinically. Return of function after intraspinal repair of ruptured nerve roots in a process involving nerve grafts has been described.⁷ After nerve root avulsion and reimplantation of nerve grafts into the spinal cord, good restoration of function in shoulder and proximal arm muscles has been reported.^{3,5,6} In this report, we present the case of a preadolescent boy in whom injury had caused complete brachial plexus avulsion. Medullary implantation of nerve grafts, to reconnect the lower cervical cord to the avulsed brachial plexus, was performed. For the first time, recovery of hand function after such devastating injury was demonstrated. The surgery-related outcome in relation to recovery of motor function, muscle synkinesis with breathing (the so-called “breathing arm”), and alleviation of pain are discussed.

Abbreviation used in this paper: EMG = electromyography.

CASE REPORT

History. This 9-year-old boy sustained a motorcycle accident–induced complete right-sided C5–T1 brachial plexus avulsion injury. He underwent follow-up examination as a part of a study at the Royal National Orthopaedic Hospital involving patients with brachial plexus injuries. Neurophysiological studies were performed at the Hammersmith Hospital in London. Ethical permission for this study was obtained from the local research ethical committees at the Royal National Orthopaedic Hospital and the Hammersmith Hospital.

Examination. Limb power was assessed using the standard Medical Research Council scale.¹⁸ Electromyography was performed using surface electrodes with a Keypoint work (Medtronic Functional Diagnostic A/S, Skovlunde, Denmark). Single-pulse transcranial magnetic stimulation was performed using Magstim 200 Monophasic stimulator (Novametrix Medical Systems Ltd., Whitland, UK). The stimulating coil was placed over the left and right motor cortex where the maximal and consistent motor evoked response was obtained. Motor evoked potentials were produced using 100% stimulus output with facilitation. The amplitude and latency data were analyzed. Quantitative sensory and autonomic tests were performed as previously described.¹

Initially there was no motor or sensory function in the right upper extremity; Tinel sign was absent in the posterior triangle of the neck. A Horner sign was present. Computerized tomography myelography revealed a complete C5–T1 avulsion injury (Fig. 1). An electrophysio-

Fig. 1. Computerized tomography myelography demonstrating avulsion cysts corresponding to right-sided C5–T1 nerve roots. Contours of roots are shown on the left side.

logical study demonstrated no motor function but the presence of sensory action potentials in accordance with nerve root injuries. The patient suffered severe constant pain (Grade 8 [of 10] on the visual analog scale) and attacks of shooting pain. Pain was located in the entire limb, and was treated (gabapentin 1600 mg/day) with modest benefit.

Operation. The patient underwent surgery 4 weeks postinjury. He was positioned laterally on the operating table to allow for a simultaneous approach to the extra- and intraspinal parts of the brachial plexus (for details regarding surgical exploration, see our previous description).⁵ The entire plexus had been avulsed with nerve roots and ganglia found beneath the clavicle. The phrenic nerve was intact and shown to be functional on electrical stimulation. After a dissection through the lateral neck muscles, respecting the accessory nerve, a C4–C7 hemilaminectomy was performed. After the dura mater was opened, a complete avulsion of C5–T1 nerves was verified with no root remnants. The superficial radial nerve was reached through a separate skin incision along the radial aspect of the forearm. The dislodged brachial plexus was dissected and mobilized toward the cervical spine. Nerve grafts were pulled into the spinal canal through the intervertebral C-7 foramen (Video Clip).

Click here to view Video Clip 1. The first part demonstrates the surgical technique for implanting a peripheral nerve graft (the sensory branch of the radial nerve) into the cervical spinal cord. The nerve graft connects the extraspinal brachial plexus to the spinal cord and is first pulled through an intervertebral foramen guided by a silicone catheter. Stay sutures are applied to the denticulate ligament to rotate the spinal cord gently. Small slits are produced in the anterolateral aspect of the spinal cord to receive the ends of the nerve transplants inserted to a depth of 1 to 2 mm by using a Roton instrument. Tisseal glue is applied to hold the nerve grafts attached to the spinal cord.

The second part shows the return of function in the patient's arm approximately 15 months postoperatively, and the final part depicts hand function approximately 1 year later.

Three strands of the nerve graft were implanted through multiple small slits in the anterior part of the spinal cord to a depth of approximately 1 mm, as measured using a Roton instrument. The position of the implanted nerve grafts was maintained using Tisseal glue (Video Clip). The nerve grafts were distally connected to the motor parts of the upper, middle, and lower trunks of the brachial plexus. Nerve transfers were also performed: the accessory nerve was transferred to the suprascapular nerve, a cervical plexus motor branch was transferred to the upper trunk, and supraclavicular sensory nerves were joined to the sensory parts of the C-7, C-8, and T-1 spinal nerves. The dura was closed, and the wound was closed in layers. The neck was immobilized in a hard collar and the arm immobilized in a sling for 6 weeks.

Postoperative Course. Muscle recovery started approximately 8 to 10 months after surgery at the shoulder and elbow. Two years postoperatively there was normal power (Grade 5/5) in the trapezius and serratus anterior muscles. Good power (Grade 4/5) was noted in the deltoid and biceps muscles as well as in forearm, wrist and finger flexors. There was some function (Grade 2/5) in triceps and intrinsic hand muscles, but no clinical function in wrist,

and finger extensors. Hand function, with the ability to grasp, make a fist, and pinch, had recovered (Video Clip). There were obligatory cocontractions of all recovered muscles on volition, as well as inspiration-induced cocontractions of recovered proximal arm muscles (Table 1). There was perception of touch, proprioception, and vibration in the region of the shoulder and elbow, at elevated thresholds when using quantitative sensory testing, but no sensation in the distal part of the arm and hand. There was no sudomotor function in the hand, measured using an evaporimeter. Touch-evoked sensation in the ipsilateral clavicular region was referred to the hand. In conjunction with return of motor function, beginning approximately 8 to 10 months after surgery, pain disappeared completely and gabapentin was no longer needed.

Electromyography showed good recruitment of motor units in pectoral, deltoid, triceps, and biceps muscles, wrist and finger flexors, and in intrinsic muscles of the hand (Fig. 2 upper). There were cocontractions of all muscles (Fig. 2 center), and inspiration-evoked muscle activity was demonstrated in biceps, triceps, deltoid, and pectoral muscles (Fig. 2 lower). Transcranial magnetic stimulation produced muscle responses in all of the afore-listed muscles, with prolonged latency and smaller amplitude except in the pectoral muscle, in which the amplitude was comparable with the intact side (Fig. 3).

DISCUSSION

The results in this case confirm the previously established concept that intraspinal repair of ruptured or avulsed ventral nerve roots can lead to nerve regeneration and restoration of function in the affected limb. A novel finding of particular interest is the return of function in the distal arm and hand. Transcranial magnetic stimulation demonstrated connectivity from motor cortex to the previously denervated muscles in this case, through the reconstructed spinal cord–peripheral nerve trajectories. The latency of the muscle response was generally longer than that in the intact arm indicating that the regenerated myelinated nerve fibers were not fully mature on the lesioned side. These findings were observed in a case of a preadolescent individual, with concomitant alleviation of pain; in a similar adult case with complete brachial plexus avulsion and intraspinal repair, recovery was restricted to the proximal part of the arm, and pain persisted distally in the nonfunctional arm and hand.

The clinical observation of superior nerve regeneration and return of function in children rather than adults²⁰ has been verified electrophysiologically.¹⁴ Motor axons regen-

erate faster in young than mature animals.¹² The mechanisms underlying this age difference are largely unknown, but better axonal guidance, as well as plasticity, have been indicated. The patient in the present case and the aforementioned adult patient, however, both exhibited persisting cocontractions and respiratory synkinesis, indicating poor axonal guidance and plasticity.

The functional gain due to intraspinal repair of brachial plexus avulsion is limited by muscle cocontractions. The lack of guidance of nerve regeneration causes aberrant muscle reinnervation. In the present case, in which the injury and repair site were within the spinal cord, synkinesis could result from several axons being produced by the same motor neuron (that is, supernumerary axons).¹⁵ In previous primate studies, investigators demonstrated a random reinnervation of arm muscles from the normally discrete and topographically arranged populations of motor neurons.¹³ This lack of appropriate muscle reinnervation applies also to the phrenic motor neurons regenerating in arm muscles, causing respiratory-related limb muscle contractions.

The so-called breathing arm was described by Erb more than 100 years ago.²² Elbow flexion with respiration has been described in patients in whom nerve transfers were performed for severe brachial plexus injuries, particularly transfer of intercostal nerves.¹⁷ To our knowledge, this is the first time the so-called breathing arm phenomenon has been described after spinal cord repair of root avulsions. Synkinesis was observed only during inspiration. The sources of this activity are the phrenic nerve motor neurons, which are situated at the C3–5 spinal cord segments, in a discrete nucleus in the most medial part of the ventral horn, adjacent to the motor neurons supplying the shoulder and upper part of the arm. Implantation of a peripheral nervous system conduit into the ventral part of the C-5 spinal cord segment could thus allow regeneration of the phrenic nerve motor neurons within this segment to the arm instead of the diaphragm. The so-called breathing arm phenomenon in this patient, and the similar adult case, demonstrates intramedullary as well as spinal cord to peripheral nerve regeneration permitted by this surgery.

The successful outcome in this and the adult case (in which surgery was performed 4 days after injury) was dependent on swift intervention rather than initial conservative management. Restoration of function depends on the survival of motor neurons after ventral root avulsion, a crucial initial regeneration process through central nervous system tissue in the spinal cord, and then further axonal growth along the peripheral nerves. Nerve root avulsion produces an extensive loss of motor neurons

TABLE 1
Muscle power demonstrated at follow-up examination*

Muscle Strength	Muscle Power								ADM T-1
	Pect C5–T1	Delt, SS C-5	LD C-6, C-7	Biceps C-6	Triceps C-6, C-7	FCR C-6, C-7	FCU C-7, C-8	FDP C-8, T-1	
MRC grade†	5c, b	5c, b	4c	4c, b	2c, b	3c	4c	4c	2c

* ADM = abductor digiti minimi; delt = deltoid muscle; FCR = flexor carpi radialis; FCU = flexor carpi ulnaris; FDP = flexor digitorum profundus; LD = latissimus dorsi; pect = pectoral muscle; MRC = Medical Research Council; ss = supra scapularis.
† Letters indicate cocontractions (c) and/or breathing arm activity (b).

Fig. 2. Electromyography studies. *Upper*: Motor unit potential recorded from the abductor digiti minimi muscle on maximal voluntary effort. *Center*: Multichannel EMG recording of cocontracting muscles in the right upper limb (amplitude 0.5 mm/division, latency 160 msec/division). *Lower*: Multichannel EMG recording of muscles in the right upper limb showing bursts of motor units firing synchronously with inspiration. An electrocardiographic artefact is also seen (amplitude 0.5 mm/division, latency 2 seconds/division). ADM = abductor digiti minimi.

Fig. 3. Motor responses from transcranial magnetic stimulation from the affected (*upper*) and unaffected (*lower*) side. Note the reduced amplitude and increased latency of the response from the abductor digiti minimi on the affected side.

within the 1st month after trauma.¹⁶ The lack of trophic support from target muscle fibers and Schwann cells in the peripheral nerve is recognized as a major cause of cell death. Regrowth of new axons is determined to a large extent by processes that occur immediately after the injury.¹¹ There is a rapid increase in secretion of growth factors by glial cells, as well as secondarily from recruited blood-borne cells,⁴ consequent to the trauma. Because of the biological factors that occur after nerve injury therefore underscore urgency of nerve repair, the optimal time for surgery is close to the time of injury.

Sensory recovery is poor after this type of surgery, when only motor conduits have been reconstructed. We found that sensation referred from the region of the neck to the hand was present in our patient, and this may reflect central nervous system plasticity. The lack of sensory reconnection with pertinent spinal cord segments results in lack of muscle proprioception. Limb functions, and in particular purposeful movements, have been described in a rare example of a sensory neuropathy with loss of muscle afferents.⁸ The patient in that case could learn to compensate for the loss of perception of muscle function or movements with other sensory inputs, such as vision.

The severe pain experienced by patients who have sustained brachial plexus avulsion injury is characteristic¹⁰ and is presumed to be caused by the generation of abnormal activity in deafferented spinal cord segments.²¹ It has recently been described that transfer of nerves to the avulsed brachial plexus was related to amelioration of pain, particularly with return of muscle function; the potential mechanisms have been discussed previously.² This

observation is certainly supported in the present study, as the patient recovered muscle activity in all parts of his upper extremity, but exhibited very limited sensory function, and experienced complete alleviation of his severe pain when muscle function recovered.

In the present case in which the C5–T1 brachial plexus was completely avulsed from the spinal cord, we found clinical and electrophysiological (EMG and transcranial magnetic stimulation) evidence of the efficacy of spinal cord reimplantation surgery. The treatment-related alleviation of pain is an important feature. The restoration of motor function of the hand demonstrates the potential of this approach in reconstructing intraspinal neural networks. An obvious immediate objective would be to improve further the functional outcome after this spinal cord surgery, with novel treatments that may rescue injured neurons and enhance nerve regeneration.

References

1. Anand P, Terenghi G, Warner G, et al: The role of endogenous nerve growth factor in human diabetic neuropathy. **Nat Med** 2: 703–707, 1996
2. Berman JS, Birch R, Anand P: Pain following human brachial plexus injury with spinal cord root avulsion and the effect of surgery. **Pain** 75:199–207, 1998
3. Bertelli JA, Ghizoni MF: Brachial plexus avulsion injury repairs with nerve transfers and nerve grafts directly implanted into the spinal cord yield partial recovery of shoulder and elbow movements. **Neurosurgery** 52:1385–1390, 2003
4. Brecknell JE, Fawcett JW: Axonal regeneration. **Biol Rev Camb Philos Soc** 71:227–255, 1996
5. Carlstedt T, Anand P, Hallin R, et al: Spinal nerve root repair and reimplantation of avulsed ventral roots into the spinal cord after brachial plexus injury. **J Neurosurg (Spine 2)** 93: 237–247, 2000
6. Carlstedt T, Grane P, Hallin RG, et al: Return of function after spinal cord implantation of avulsed spinal nerve roots. **Lancet** 346:1323–1325, 1995
7. Carlstedt T, Noren G: Repair of ruptured spinal nerve roots in a brachial plexus lesion. Case report. **J Neurosurg** 82:661–663, 1995
8. Cole JD, Sedgwick EM: The perceptions of force and movement in a man without large myelinated sensory afferents below the neck. **J Physiol** 449:503–515, 1992
9. Cullheim S, Carlstedt T, Risling M: Axon regeneration of spinal motoneurons following a lesion at the cord-ventral root interface. **Spinal Cord** 37:811–819, 1999
10. Frazier CH, Skillern PG Jr: Supraclavicular subcutaneous lesions of the brachial plexus not associated with skeletal injuries. **J Am Med Assoc** 57:1957–1963, 1911
11. Fu SY, Gordon T: The cellular and molecular basis of peripheral nerve regeneration. **Mol Neurobiol** 14:67–116, 1997
12. Gutmann E: Factors affecting recovery of motor function after nerve lesions. **J Neurol Psychiatry** 5:81–95, 1942
13. Hallin RG, Carlstedt T, Nilsson-Remahl I, et al: Spinal cord implantation of avulsed ventral roots in primates; correlations between restored motor function and morphology. **Exp Brain Res** 124:304–310, 1999
14. Hallin RG, Wiesenfeld Z, Lungnegard H: Neurophysiological studies of peripheral nerve functions after neural regeneration following nerve suture in man. **Int Rehabil Med** 3:187–192, 1981
15. Havton L, Kellerth JO: Regeneration by supernumerary axons with synaptic terminals in spinal motoneurons of cats. **Nature** 325:711–714, 1987
16. Koliatsos VE, Price WL, Pardo CA, et al: Ventral root avulsion: an experimental model of death of adult motor neurons. **J Comp Neurol** 342:35–44, 1994
17. Malessy MJ, van Dijk JG, Thomeer RT: Respiration-related activity in the biceps brachii muscle after intercostal-musculocutaneous nerve transfer. **Clin Neurol Neurosurg** 95 (Suppl):S95–S102, 1993
18. Medical Research Council: **Aids to the Examination of the Peripheral Nervous System. Memorandum No 45.** London: HMSO, 1976
19. Narakas AO: Thoughts on neurotization or nerve transfers in irreparable nerve lesions. **Clin Plast Surg** 11:153–159, 1984
20. Onne L: Recovery of sensibility and sudomotor function in the hand after nerve suture. **Acta Chir Scand** 300 (Suppl):1–69, 1962
21. Ovelmen-Levitt J: Abnormal physiology of the dorsal horn as related to the deafferentation syndrome. **Appl Neurophysiol** 51:104–116, 1988
22. Swift TR: The breathing arm. **Muscle Nerve** 17:125–129, 1994

Manuscript received March 8, 2004.

Accepted in final form April 2, 2004.

This work was supported by the International Spinal Research Trust (grant no. STR 059).

Address reprint requests to: Thomas Carlstedt, M.D., The Periphery Nerve Injury Unit, The Royal National Orthopaedic Hospital, Brockley Hill, Stanmore HA7 4LP, United Kingdom. email: Thomascarlstedt@fsmail.net.