Surgical Restoration of Arm and Hand Function in People with Tetraplegia

Anne M. Bryden, OTR/L,[1] *Allan E. Peljovich, MD, MPH,*[2,3] *Harry A. Hoyen, MD,*[1,4] *Gregory Nemunaitis, MD,*[4,5] *Kevin L. Kilgore, PhD,*[1,4,6] *and Michael W. Keith, MD*[1,4,6]

[1]*The Cleveland FES Center, Case Western Reserve University, Cleveland, Ohio;* [2]*The Hand and Upper Extremity Center of Georgia, Atlanta, Georgia;* [3]*The Shepherd Center, Atlanta, Georgia* [4]*MetroHealth Medical Center, Cleveland, Ohio;* [5]*MetroHealth Rehabilitation Institute of Ohio, Cleveland, Ohio;* [6]*Louis Stokes Cleveland Veterans Affairs Medical Center, Cleveland, Ohio*

Improved hand and arm function is the most sought after function for people living with a cervical spinal cord injury (SCI). Surgical techniques have been established to increase upper extremity function for tetraplegics, focusing on restoring elbow extension, wrist movement, and hand opening and closing. Additionally, more innovative treatments that have been developed (implanted neuroprostheses and nerve transfers) provide more options for improving function and quality of life. One of the most important steps in the process of restoring upper extremity function in people with tetraplegia is identifying appropriate candidates – typically those with American Spinal Injury Association (ASIA) motor level C5 or greater. Secondary complications of SCI can pose barriers to restoring function, particularly upper extremity spasticity. A novel approach to managing spasticity through high-frequency alternating currents designed to block unwanted spasticity is being researched at the Cleveland FES Center and may improve the impact of reconstructive surgery for these individuals. The impact of these surgeries is best measured within the framework of the World Health Organization's *International Classification of Function, Disability and Health*. Outcome measures should be chosen to reflect changes within the domains of body functions and structures, activity, and participation. There is a need to strengthen the evidence in the area of reconstructive procedures for people with tetraplegia. Research continues to advance, providing more options for improved function in this population than ever before. The contribution of well-designed outcome studies to this evidence base will ultimately help to address the complications surrounding access to the procedures. **Key words:** *denervation, neuroprostheses, reconstructive procedures, tendon transfers, tetraplegia, spinal cord injury, upper extremity*

The loss of arm and hand function as a result of traumatic cervical spinal cord injury (SCI) results in the immediate inability to perform even simple activities of daily living (ADLs). Every year in the United States, there are approximately 12,000 new incidences of SCI. Fifty-six percent of these cases result in tetraplegia, with C5 being the most common injury level.[1] Increased arm and hand function is an important rehabilitation goal for most individuals with tetraplegia. In fact, it is the most sought after function for this population. Anderson reports that 48.7% of 347 people with cervical level SCI felt that gaining arm and hand function would significantly improve their quality of life and prioritized it over regaining sexual function, trunk stability, bowel and bladder control, and walking.[2] Similarly, Snoek reports that 77% of 565 people with tetraplegia in England and The Netherlands expected an important or very important improvement in quality of life as a result of improved hand function.[3] Surgical techniques have been established to increase upper extremity function for these individuals.[4-8] These procedures focus on restoring elbow extension, wrist movement, and hand opening and closing with the goal of increasing independence in ADLs. Newer innovations such as neuroprostheses[9] and nerve transfer procedures further expand the potential for reanimating the upper extremity in this population.

"The greatest potential for improving the quality of life lies with rehabilitation and restoration of upper extremity function."[10 (p86)] Despite the recognition of the merit of reconstructive procedures by rehabilitation professionals and the reported desire for improved arm and hand function by people with tetraplegia, the procedures are underutilized.[11-14] The reasons appear multifactorial. Too few surgeons and physiatrists are paying attention to the hand and upper extremity. One factor is a lack of interest and interdisciplinary associations between surgeons

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Table 1. Classification systems for tetraplegia

ASIA	Key muscle (grade 3)	IC motor group	Key muscle (grade 4)
C4 and higher		NA	
C5	Biceps	0	Biceps
		1	Brachioradialis
C6	ECRL	1	Brachioradialis
		2	ECRL
		3	ECRB
		4	PT
C7	Triceps	4	PT
		5	FCR
		6	EDC
		7	EPL
C8	FDP	8	FDS
		9	FDS and FDP

Note: ASIA = American Spinal Injury Association; ECRB = extensor carpi radialis brevis; ECRL = extensor carpi radialis longus; EDC = extensor digitorum communis; EPL = extensor pollicis longus; FCR = flexor carpi radialis; FDP = flexor digitorum profundus; FDS = flexor digitorum superficialis; NA = not applicable; PT = pronator teres.

and physiatrists. Additionally, misconceptions persist that people with tetraplegia tend to be noncompliant with treatment and lack the resources and support to carry out rehabilitative protocols. Physicians also seem to be under the impression that third party payers do not reimburse for treatment of the hand and upper extremity in the setting of SCI. As a result, these misconceptions limit access to opportunities for improved arm and hand function for people with tetraplegia. Continued dissemination of information about the importance of hand and upper extremity rehabilitation in the tetraplegic population will contribute to improved access to these types of procedures for more individuals with tetraplegia.

Candidate Selection

The most important step in the process of restoring upper extremity function in people with tetraplegia is identifying appropriate candidates. Due to the rigid medical and psychosocial criteria, approximately 60% of people with tetraplegia are candidates.[14-16] Candidates with an American Spinal Injury Association (ASIA)[17] motor level of C5 or greater are typically candidates. Additional criteria include neurological stability, plateau of functional gains, good motivation with appropriate goals for improved function, good general health, supple upper extremity joints that are free of contracture, well-controlled spasticity, and good seating and trunk stability to allow use of the upper extremity.

To assist in surgical planning for this population, a more comprehensive classification system of cervical spinal cord injury was developed. The International Classification for Surgery of the Hand in Tetraplegia (ICSHT)[18] was specifically developed to identify candidates for upper extremity restoration. This classification provides information about the number of voluntary muscles available for surgical transfer to provide another function lost from paralysis. The strength of the key muscle for each level of the classification must be rated as grade 4 in order to receive that designation. For example, someone with a C5 level injury could be classified as ICSHT group 0 if the brachioradialis muscle (a muscle frequently chosen for tendon transfer) is less than grade 4 or as ICSHT group 1 if the brachioradialis is rated as grade 4 or 5. There is also a sensory component of this classification, denoting whether the person has cutaneous sensation in the thumb (Cu) or must rely on ocular compensation for lack of sensation (O). **Table 1** shows an overview of the ICSHT in comparison with the ASIA classification.

A comprehensive physical assessment is required to identify the best approach toward restoring function. This includes a full evaluation of upper extremity active range of motion, passive range of motion, and strength, including the shoulder and scapular muscles. An important component of the evaluation includes characterizing paralysis. As the zone of injury can include both the cord and the peripheral nervous system about the neck, varying patterns of nerve injury are manifest. Above the zone of injury, the central and peripheral systems and their interconnections are intact and fully functional. Below this zone, the nerve pathophysiology resembles an upper motor neuron lesion with hyperreflexia. Within the zone of injury, which can extend from the spinal cord to the level of the dorsal sensory ganglia and nerve roots, the pattern of nerve loss is a combination of pure upper motor neuron and lower motor neuron and sensory involvement. Understanding the type of paralysis is important in planning intervention and preventing the onset of secondary complications such as joint stiffness and contracture. In the zone of injury, lower motor neuron involvement or peripheral nerve damage results in muscles that are flaccid, without natural spasms, and do not respond to electrical stimulation as the paralyzed muscles with only upper motor neuron involvement do. Paralysis from upper and lower motor neuron involvement pose greater risk for contracture development.[11] The integrity of the lower motor neuron can be easily evaluated using a surface electrical stimulation unit. If there is a good response to stimulation in the paralyzed muscles, then the lower motor neuron is intact. This opens up other opportunities for treatment such as the use of surface FES to improve hand posture/tenodesis or more permanent interventions such as a neuroprosthesis. Poor response to stimulation indicates pathology in the lower motor neuron, which is valuable information as preventative measures such as stretching and splinting can be put into place to avoid joint contractures.

Surgical Planning

Surgical planning is a process that is individualized to each surgery candidate. The first principle of reconstruction is to build upon the tenodesis effect, where passive finger and thumb flexion occur with wrist extension, providing the ability to pick up light objects. For example, someone with an ASIA C5/ICSHT O/Cu:1 classification would benefit from a transfer of the brachioradialis muscle to the extensor carpi radialis brevis (ECRB) to provide active wrist extension and a tenodesis grasp. For stronger individuals who already have wrist extension, the brachioradialis muscle could be transferred into the FPL to provide active thumb pinch. **Table 2** lists examples of tendon transfer and other reconstructive procedures for each cervical level of injury. A second principle focuses on expanding the workspace for the person with tetraplegia. This is most commonly done by providing active elbow extension where it is absent. Historically, either the posterior portion of the deltoid muscle or a portion of the biceps has been transferred into the paralyzed triceps to accomplish this. Recent studies have identified that better outcomes occur with the biceps to triceps tendon transfer, and this has now become the favored transfer in clinical practice.[6,19]

A third principle of reconstruction is to use functional electrical stimulation (FES) to provide function where other reconstructive procedures cannot. This is a particular benefit for people with higher level injury who do not have voluntary muscles available for transfer, as is the case for those with an ASIA C5/ICSHT group 0 classification. Researchers at The Cleveland FES Center continue to develop implanted upper extremity neuroprostheses for people with tetraplegia. Current systems include the ability to stimulate 12 muscles for function and record from 2 muscles to control stimulation.[9] An external control unit is used to power the system. In the near future, a completely implanted system will be available, eliminating the need to connect to an external device to power the system.[20,21] This new technology will provide more flexibility in restoring not only arm and hand function but also other functions critical to people with tetraplegia

Table 2. Reconstructive surgery options

Level of injury ASIA/ICSHT	Procedure	Function gained
C5, O/Cu:1	BR-ECRB	Active wrist extension
	FPL tenodesis	Static thumb pinch
	Biceps-Triceps	Active elbow extension
C6, O/Cu: 1 or 2	Br-FPL	Active thumb pinch
	EPL tenodesis	Static thumb extension
	Biceps-Triceps	Active elbow extension
C6, O/Cu:3	Br-FPL	Active thumb pinch
	ECRL-FDP	Active finger flexion
	EPL tenodesis	Static thumb extension
	EDC tenodesis	Static finger extension
	Biceps-Triceps	Active elbow extension
C7, O/Cu:4 or 5	Br-FPL	Active thumb pinch
	EPL tenodesis	Static thumb extension
	ECRL-FDP	Active finger flexion
	PT-EDC	Active finger extension
C7, O/Cu:6	Br-FPL	Active thumb flexion
	PT-EPL (or)	Active thumb extension
	Opponensplasty via PT	Active thumb opposition
	ECRL-FDP	Active finger flexion
C7, O/Cu:7	BR-FPL	Active thumb flexion
	Opponensplasty via PT	Active thumb opposition
	ECRL-FDP	Active finger flexion
C7/C8, O/Cu:8 or 9	Zancolli lasso procedure	Prevents MP hyperextension

Note: ASIA = American Spinal Injury Association; Br = brachioradialis; ECRB = extensor carpi radialis brevis; ECRL = extensor carpi radialis longus; EDC = extensor digitorum communis; EPL = extensor pollicis longus; FDP = flexor digitorum profundus; FPL = flexor pollicis longus; ICSHT = International Classification for Surgery of the Hand in Tetraplegia; MP = metacarpal-phalangeal joint; PT = pronator teres.

such as trunk stability, bowel and bladder function, and the ability to cough. The new technology will facilitate restoration of multiple functions in people with tetraplegia.

Unfortunately, not all people with tetraplegia are candidates for an upper extremity neuroprosthesis due to denervation or lower motor neuron damage. A potentially better surgical alternative for restoring function in the presence of denervation is a nerve transfer for reinnervation. If innervation is restored to denervated muscles quickly after injury, both voluntary function and response to electrical stimulation have a chance to be restored. The techniques of neurotization in the upper extremity for people with tetraplegia have been modeled after the techniques used in individuals with brachial plexus injuries.[22–25] One of the challenges in implementing these techniques in people after SCI is the necessity of initiating the procedures early after injury in order for them to be successful. Often, the permanence of the injury has not been realized within the time frame for the nerve transfer to be the most successful, generally within about 6 months. Further study is required to improve prognostication techniques and identify instances where nerve transfer is the only reasonable attempt at recovering function.

Barriers to Restoring Upper Extremity Function

Despite the availability of some of the best surgical procedures and technology, there can be barriers to restoring upper extremity function in people with tetraplegia. Rehospitalization rates for this population are high at 74% because of urinary complications, systematic follow-up, pressure sores, respiratory complications, contractures, bowel complications, pain, and fractures.[26] Many of these complicating factors can delay or even prevent efforts for restoring upper extremity function. In a large scale survey of 1,668 people with SCI, 85% complained of awkward contractures.[26] People with tetraplegia are at risk for contracture development in the upper extremity, particularly if there are high levels of spasticity in muscles whose antagonists present with lower motor neuron damage.[11]

Researchers at The Cleveland FES Center are investigating a novel way to reduce spasticity, one of the primary limitations to upper extremity restoration. Conventional methods of reducing spasticity such as oral or intrathecal medications like baclofen can have significant side effects[27,28] and require close monitoring.[29,30] Kilgore et al are investigating a technique utilizing a novel electrical stimulation waveform, high-frequency alternating currents (HFAC), as an alternative to conventional methods of managing spasticity.[31] Benefits of this nerve block technique are that it is fast-acting (it can be turned on immediately following the detection of the start of a spasm) and it is quickly reversible (the nerve is not blocked during the absence of a spasm in order to maintain residual muscle tone). Research of this technique is continuing to determine whether the block is safe for chronic use with minimal side effects.

Measuring Outcomes Following Upper Extremity Reconstruction

Determining the impact of upper extremity restoration is paramount. The World Health Organization's (WHO) *International Classification of Function, Disability and Health* (ICF)[32] provides a framework for the interpretation of outcomes after upper extremity restoration efforts. The following domains of the ICF are useful in guiding the choice of measures: body functions and structures, activity (capacity and performance), and participation.[33,34] To date, there are still challenges in measuring the impact of surgery. Problems identified in previous studies include the following: (1) standard measure are not consistently used, (2) measures used are not available or not easily used in clinical settings, (3) measures are used only for a specific study, and (4) outcomes are based solely on subjective reports of satisfaction.[35] All of these issues make it difficult to compare results across the numerous studies performed with small numbers of participants. As a result, there is increased need for studies with higher levels of evidence. This had led to considerable debate about the merit of well-designed observational studies compared to randomized controlled trials.[36] Ultimately, there is the need to strengthen the evidence overall by improving study design. When possible, a randomized controlled trial should be the goal, however, a well-designed observation study should be accepted as the next best option. Additionally, a consensus should be reached on the appropriate measures for use in multicenter trials, and the psychometric properties of existing measures should be strengthened.

Conclusion

In summary, there are many options available for improved arm and hand function for people with tetraplegia. Greater function can be achieved by moving voluntary muscles, tightening paralyzed muscles, and activating paralyzed muscles with electrical stimulation. Research continues to advance, providing more options for improved function in this population than ever before. The contribution of well-designed outcome studies to the evidence base for tetraplegic upper extremity reconstruction will ultimately help to address the complicated problem of poor access to the procedures.

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