OPEN

PRS GLOBAL OPEN

ORIGINAL ARTICLE
Hand/Peripheral Nerve

Neuroplasticity following Nerve Transfer of the Anterior Interosseous Nerve for Proximal Ulnar Nerve Injuries

Erika Nyman, MD, PhD*†
Torbjörn Nyman, MD*‡
Carin Rubensson, MD*†
Magnus Thordstein, MD, PhD*§

Background: Injuries to the ulnar nerve at or above proximal forearm level result in poor recovery despite early microsurgical repair, especially concerning the intrinsic motor function of the hand. To augment the numbers of regenerating axons into the targeted muscles, a nerve transfer of the distal branch of the median nerve, the anterior interosseous nerve, to the ulnar motor branch has been described.
Methods: Two patients with severe atrophy of the intrinsic hand muscles following an initial proximal ulnar nerve repair had surgery with an end-to-side transfer of the anterior interosseous nerve to the ulnar motor branch at the wrist level. Outcome and neuroplasticity were prospectively studied using questionnaires, clinical examinations, electroneurography, electromyography, somatosensory evoked potentials at pre nerve transfer and 3-, 12-, and 24-months post nerve transfer as well as navigated transcranial magnetic stimulation at pre nerve transfer and 3- and 12-months post nerve transfer.
Results: Successively improved motor function was observed. Complete reinnervation of intrinsic hand muscles was demonstrated at 12- to 24-months follow-up by electroneurography and electromyography. At the cortical level, navigated transcranial magnetic stimulation detected a movement of the hot-spot for the abductor digiti mini muscle, originally innervated by the ulnar nerve and the size of the area from where responses could be elicited in this muscle changed over time, indicating central plastic processes. An almost complete reinnervation of the pronator quadratus muscle was also observed.
Conclusion: Both central and peripheral plastic mechanisms are involved in muscle reinnervation after anterior interosseous nerve transfer for treatment of proximal ulnar nerve injuries. *(Plast Reconstr Surg Glob Open 2021;9:e3684; doi: 10.1097/GOX.0000000000003684; Published online 13 July 2021.)*

*From the *Department of Biomedical and Clinical Sciences, Linköping University, Linköping, Sweden; †Department of Hand Surgery, Plastic Surgery and Burns, and Department of Biomedical and Clinical Sciences, Linköping University Hospital, Linköping, Sweden; ‡Department of Pain and Rehabilitation Medicine and Department of Biomedical and Clinical Sciences, Linköping University Hospital, Linköping, Sweden; and §Department of Clinical Neurophysiology, Department of Neurobiology, and Department of Biomedical and Clinical Sciences, Linköping University, Linköping, Sweden.*

Received for publication January 25, 2021; accepted May 5, 2021.

Presented orally in part at the 24th Sunderland Society Meeting, 2019, Jerusalem, Israel; the Swedish Society for Surgery of the Hand (FESSH) – Annual Meeting, 2019, Sigtuna, Sweden; and the Federation of the European Societies for Surgery of the Hand (Digital Meeting), 2020.

DOI: 10.1097/GOX.0000000000003684

INTRODUCTION

Ulnar nerve injuries are well-known surgical challenges that often result in sensory and motor dysfunction to various extents, and even in severe atrophy of the target muscles, despite early microsurgical nerve repair or reconstruction.[1–4] A proximal ulnar nerve injury at forearm or elbow level normally results in even more disability than a distal injury at the wrist level. Outcome of standard surgery is poor, especially concerning the intrinsic motor function of the hand essential for fine motor skills.[1,2,5,6] Nerve regeneration is as slow as approximately 1 mm per day.[7] Therefore, the use of a distal nerve transfer may provide a strategy to bypass the problems associated with a long distance for axonal outgrowth, augment the number of regenerating axons into the muscle, and reduce the time to reinnervation.[8,9]

Disclosure: *All the authors have no financial interest to declare in relation to the content of this article. This study was supported by ALF Grants (register number LIO-823361, LIO-936176, 897191), Region Östergötland, Sweden.*

Related Digital Media are available in the full-text version of the article on www.PRSGlobalOpen.com.

To improve function of intrinsic hand muscles after a proximal ulnar nerve injury, a nerve transfer of one of the distal branches of the median nerve was proposed. Connecting the anterior interosseous nerve (AIN), originally innervating the pronator quadratus (PQ) muscle, to the ulnar motor branch at wrist level was described as a successful procedure with low morbidity.[10–12] The AIN transfer has been refined to be performed via an epineural window in an end-to-side nerve repair, "supercharge," instead of an end-to-end coaptation of the nerve endings.[13–15] This way, axonal regeneration is intended to be enhanced without disrupting the ulnar nerve recovery. Experimental studies have demonstrated axonal outgrowth from the donor nerve through the epineural window and into the recipient nerve, but the basic mechanisms behind the recovery following an end-to-side nerve transfer are not fully understood.[16,17] Most studies describing the positive effect of the AIN transfer are retrospective and lack quantitative methods of assessment. Recently, an enhanced recovery of intrinsic muscle function following an ulnar nerve repair with addition of an AIN transfer compared with an isolated proximal ulnar nerve repair was demonstrated,[18] but the involved mechanisms were not clarified.

The human brain is capable of reorganization following injury, demonstrated for median and ulnar nerve lesions[19,20] and for nerve transfers at the spinal nerve root level in animals and humans.[21,22] To explore the neuro anatomy and physiological mechanisms of central plasticity, navigated transcranial magnetic stimulation (nTMS) may be used to probe the system with high resolution.[23–27] Based on the above, our objective was to study functional outcome and neuroplasticity following an AIN transfer to the motor branch of the ulnar nerve in patients with poor intrinsic motor recovery after a previously repaired proximal ulnar nerve injury.

METHODS

Ethical approval was obtained from the Regional Ethics Review Board, Linköping, Sweden (register number 2017/239-31). Two patients were included in the study after giving oral and written consent. Both patients had a complete ulnar nerve injury in the proximal forearm, resulting in low-grade intrinsic motor function in the hand 12 and 10 months after the initial ulnar injury, respectively, despite earlier microsurgical repair.

Subjects, Methods, and Timing of Assessment

The first patient was a 26-year-old, healthy man presenting with a complete injury to the ulnar nerve in the proximal third of his left forearm, due to fractures of the proximal radius and ulna caused by an accident during volleyball play. He was referred to our department 3 months post-injury (doctor's delay) and had surgery with anterior subcutaneous transposition and microsurgical repair of the nerve injury under loop magnification (×2.5). Twelve months post-injury (9 months post-initial nerve repair), due to poor intrinsic motor function, he was included in the study.

The second patient was an 18-year-old, healthy man presenting with a stab wound to his left proximal forearm about 8 cm distal to the medial epicondyle with a complete laceration to the ulnar nerve. He had acute microsurgical repair of the nerve injury at day 3 post-injury under loop magnification (×2.5) at our department. For the same reason as that of the first patient, he was included in the study.

Patients were evaluated using the Swedish version of the Disabilities of the Arm, Shoulder and Hand (DASH) score,[28] EuroQol (EQ-5D, including a visual analog scale for current health status (VAS, current health status),[29] Rosen score,[30] and clinical examination; pre nerve transfer, at 3-, 12-, and 24-months post transfer (Table 1). Electroneurography (ENG), electromyography (EMG), sensory evoked potentials (SEP) and nTMS were performed pre nerve transfer and at 3 and 12 months postoperatively. In addition, a restricted ENG study was performed at 24 months. An overview of the timeline is given in Figure 1.

Electroneurography

In the injured arm, standard motor and sensory nerve conduction tests of the median and ulnar nerves were performed (apparatus; Synergy Carefusion, electrodes; Nicolet Biomedical, EMG surface electrode). For the median nerve, motor potentials were recorded from the abductor pollicis brevis (APB) muscle with stimulation at wrist and elbow crease and sensory responses were recorded at the wrist with stimulation of one nerve per the thumb, index, long and ring fingers, and the radial part of the palm. Ulnar nerve motor responses were recorded from the abductor digiti minimi (ADM) muscle with stimulation at the wrist, below and above the elbow, and sensory potentials were recorded at the wrist, after stimulation of one nerve per ring and little fingers and the ulnar part of the palm. At the last visit (24 months), responses were also recorded from the ADM muscle, when stimulating the median nerve.

Electromyography

Recordings from the injured arm were obtained from the APB, the PQ, the flexor carpi radialis (all three innervated by the median nerve), the interosseus dorsalis I, and the ADM (ulnar nerve innervated). For each examined muscle, the following aspects were assessed: spontaneous electrical muscle activity (divided into fibrillations/positive waves, and other spontaneous activity, such as complex repetitive discharges), motor unit potentials (amplitude, duration, number of phases), and interference (capacity for activation at high frequency). All parameters were graded, using a semiquantitative scale consisting of: 0 (missing)/N (normal), 1 (slightly increased), 2 (moderately/strongly increased), and 3 (very strongly increased) or NA (not applicable).

Somatosensory Evoked Potentials

Responses to electrical stimulation of the median and ulnar nerves of the injured arm were recorded. Using standard surface electroencephalography (EEG) electrodes, responses were recorded over the somatosensory cortex (electrode position C3' or C4' according to the 10–20 electrode positioning system) contralateral to

Table 1. Functional Outcome after Anterior Interosseus Nerve Transfer

	Pre Nerve Transfer	3 Months Post Nerve Transfer	12 Months Post Nerve Transfer	24 Months Post Nerve Transfer
DASH*	42/4	20/3	8/5	13/20
EQ-5D	0.05/0.76	0.59/0.80	0.69/0.80	0.73/0.80
VAS† current health status	60/100	70/100	80/100	90/90
Rosen score total	0.91/1.13	1.27/1.60	1.37/2.05	1.33/1.88
Rosen score sensory domain	0.31/0.33	0.29/0.40	0.33/0.52	0.28/0.54
Rosen score motor domain	0.27/0.47	0.31/0.70	0.54/0.69	0.38/0.67
MMT‡ (radial abduction dig II, abduction dig V, adduction dig V)	2,0,0/3,3,0	4,0,0/4,4,2	4,4,0/4,4,2	4,4,0/5,4,2
Full hand grip strength (injured hand/contralateral hand, %)	40/53	34/66	55/92	49/89
Key grip (injured hand/contralateral hand, %)	43/46	38/63	46/64	56/42
Pinch grip (I, II, II) (injured hand/contralateral hand, %)	39/26	36/46	40/73	60/71
Total ROM§ dig IV	250/265	230/248	231/256	276/270
Total ROM§ dig V	170/248	240/257	250/251	279/268
Atrophy	+++/++	+++/+	+/+	+/+
Claw hand deformity	+++/+++	+/−	+/−	+/−
Pro-/supination Total ROM§	140/160	125/165	115/155	150/156

For each parameter, results are given as Patient 1/Patient 2.
*Disabilities of the Arm, Shoulder, and Hand outcome questionnaire.
†Visual Analogue Scale.
‡Manual muscle testing.
§Range of motion.

stimulation. Responses were graded in absolute terms regarding latency and amplitude.

Navigated Transcranial Magnetic Stimulation

Motor evoked potentials were obtained using nTMS over the primary motor cortex, contralateral to the injured arm, with simultaneous recording of surface EMG from index muscles for the two nerves investigated: APB (median nerve) and ADM (ulnar nerve) muscles. The technique of navigated stimulation (nTMS) using this kind of equipment (Eximia, Nexstim Ltd., Helsinki, Finland) has been described by us previously.[20]

Briefly, nTMS was based on data from a newly performed structural magnetic resonance image using a three-dimensional, freely moveable image, a tracking system with infrared light, magnetic coil (figure-of-eight with winding diameter 50 mm, biphasic pulse of 280 ms) and on a separate screen, the surface electromyograms (EMG, surface electrodes; Amdu Neuroline 720, Ballerup, Denmark). For each of the index muscles, the area for activation was found by "premapping" indicating the optimal location for activation (largest response amplitude). Here, the resting motor threshold was determined. It was defined as the electric field strength (V/m) needed to produce a muscle response with top-to-top amplitude of at least 50 μV according to the threshold defining paradigm of the equipment. Stimulus response curves were also determined. At the optimal location for activation, 12 stimuli were given at three intensity levels: 1.0, 1.25, and 1.5 resting motor threshold. Finally, the area of activation was determined. Using resting motor

	Pre nerve transfer	Time zero	3 months postop	12 months postop	24 months postop
Inclusion, informed consent	X				
Surgery		X			
Questionnaires, clinical examination, ENG[a], EMG[b] and SEP[c]	X		X	X	X
nTMS[d]	X		X	X	

[a]Electroneurography

[b]Electromyography

[c]Somatosensory Evoked Potentials

[d]navigated Transcranial Magnetic Stimulation

Fig. 1. Timeline.

threshold intensity, a large number of stimuli were given at a successively longer distance from the optimal area until a delineation of the area from where a response could be induced was produced.[31]

Surgical Procedure and Postoperative Rehabilitation

Under general anesthesia, a terminal branch of the AIN that innervates the PQ muscle was transferred end-to-side through an epineural and perineural window to the motor branch of the ulnar nerve 8–9 cm proximal to the wrist crease (Fig. 2). A nerve stimulator was used to stimulate the AIN and the motor branch of the ulnar nerve. The AIN was secured with interrupted 9-0 epineural monofilament nonabsorbable sutures in a tension-free manner with addition of fibrin glue (Tissel; Baxter, Kista, Sweden) using an operating microscope and microinstruments. The same postoperative protocol for physical therapy was used for both patients with initiation of activating the intrinsic muscles while pronating and mirror therapy to enhance motor reeducation. A splint, positioning the metacarpophalangeal joints flexed and the interphalangeal joints extended was used in between training the first 2 weeks and then at night for another 4–6 weeks. All results are given per individual in quantitative or semiquantitative terms.

RESULTS

Both patients successfully improved their intrinsic motor function gradually after surgery, with increased Rosen score and grip strength as well as reduced atrophy and claw hand deformity (Table 1). (**See figure, Supplemental Digital Content,** which displays the Rosen score over time for the two patients. "Month after surgery" represents time after injury in the first patient (X) (delayed initial surgery) and initial surgery with nerve suture but no nerve transfer in the second patient (O). The first mark on the line is the time-point just before nerve transfer. **http://links.lww.com/PRSGO/B702**.)

Patient 1 initially lost range of motion regarding pronation following the AIN transfer but recovered over time (Table 1). No other complications were noted perioperatively or postoperatively. The immediate postoperative care and rehabilitation passed well (Table 1).

For both patients, ENG, EMG, and nTMS (Table 2) demonstrated progressive motor reinnervation of hand muscles innervated by the ulnar nerve after the AIN transfer, as well as near complete reinnervation of the PQ muscle. For the intrinsic hand muscles originally innervated only by the ulnar nerve, this was found in terms of ENG investigated motor function as increasing response amplitude and conduction velocity as well as increasing number of F-responses appearing at shorter latency. For EMG, a reduced number of denervation potentials and increasing signs of reinnervation regarding the voluntarily activated motor unit potentials was seen. For the median nerve regarding hand function, all these parameters were stable.

The amplitude of the SEP from stimulation of the ulnar nerve was, for both patients, reduced at the first-, but increased at the last test postoperatively. SEP latency was unaltered (Table 2). No significant alterations were

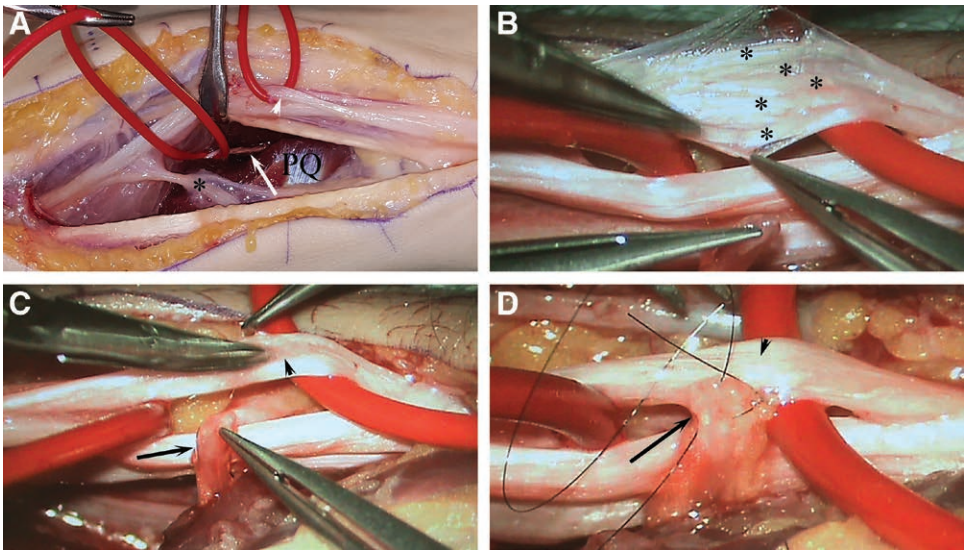

Fig. 2. Surgical procedure in the first patient. A, The motor branch of the ulnar nerve (white arrowhead) is found ulnar to the palmar sensory branch after branching of the dorsal sensory branch (black asterisk). The AIN (white arrow) is identified proximal to the PQ. The nerve is followed into the mid-portion of the muscle by dividing the overlying PQ muscle fibers and is transected distally proximal to its first branching point. B, Asterisks mark the different fascicles of the motor branch of the ulnar nerve. C, D, In a tension-free manner, the AIN (black arrows) is sutured into a wide epineural and perineural window of the motor branch of the ulnar nerve (black arrowheads) 8–9 cm proximal to the wrist crease. The procedure is performed using an operating microscope and microsurgery instruments, with 9-0 nonabsorbable epineural sutures and secured with fibrin glue.

Table 2. Neurophysiologic Assessments of (i) Degree of Reinnervation of Ulnar Hand Muscles by ENG, EMG, and nTMS and of the PQ Muscle by EMG and (ii); Global Sensory Function by Sensory Evoked Potentials (SEP) for the Ulnar and Median Nerves

		Pre Nerve Transfer	3 Months Post Nerve Transfer	12 Months Post Nerve Transfer
Motoric reinnervation of ulnar hand muscles				
	ENG (amplitude, mV)	0.5/0.1	1.7/0.2	3.9/4.4
	F response (persistence %, latency, ms)	0, NA/0, NA	60, 35/10, 55	85, 28/55, 31
	EMG (rest, slight-, maximal activation, arbitrary units)	3, 0, 2/3, 3, 3	3, 3, 2/2, 1, 3	0, 2, 3/2, 1, NA
	nTMS (response amplitude at RMT,* μV)	98/148	1422/NA	1291/220
Motoric reinnervation of PQ				
	EMG (as above)	0, 0, 0/0, 0, 0	3, 3, 3/3, 3, 3	1, 1, 0/NA
SEP				
Ulnar nerve	Amplitude (μV)	3.2/1.8	0.96/0.47	1.8/3.5
	Latency (ms)	18.9/20.9	21.2/19.8	22.8/24.2
Median nerve	Amplitude (μV)	5.7/9.9	4.1/7.7	6.6/10.8
	Latency (ms)	18.0/20.0	20.6/20.5	18.4/19.9

For each parameter, results are given as Patient 1/Patient 2. For explanation of arbitrary units of EMG, see text.
*Resting Motor Threshold.

found regarding the SEP from stimulation of the median nerve.

For both patients, regarding the parameters of corticospinal excitability, preoperatively, the absolute value of resting motor threshold was lower for the ADM than for the APB muscle (Table 3). The response amplitude at resting motor threshold was also lower. During the time of observation postoperatively, the resting motor threshold for the ADM increased and became similar to the one of the APB muscles. In parallel, the response amplitude of the ADM muscle increased. The stimulus response curves did not differ appreciably between the two muscles at any time point.

The morphology of the motor responses was evaluated both when responses were evoked centrally with nTMS and peripherally with ENG testing (Table 3). For peripheral stimulation of the median nerve and recording from the APB muscle, all responses were normal at all time points. For peripheral stimulation of the ulnar nerve and recording from the ADM muscle, the findings differed between the patients: For the first patient, a slight splitting was seen preoperatively, none at the later time points. For the second patient, with stimulation at the wrist, none was seen preoperatively, a slight at three months and again none at 12 months. With more proximal stimulation (the elbow), splitting was present at both the later time points. At the last testing (two years postoperatively) also stimulation of the median nerve with recording from the ADM muscle was performed. Here, stimulation of the ulnar nerve produced normally configured motor unit potentials. Stimulation of the median nerve also yielded normal responses from the wrist level. From the elbow level however, the response was, compared with the one from the wrist, larger and slightly more split. For central stimulation (nTMS), an opposite-like image appeared (Table 3). Over time, the degree of splitting of the APB muscle responses increased. For the ADM muscle, it decreased for the first patient and increased for the second patient.

Apart from the responses at normal latency, a separate population of late appearing muscle responses could be observed from the ADM muscle at all time points for central stimulation (Fig. 3). In general, they were elicited from the peripheral part of the cortical activation area, had low amplitude and were oligophasic. Over time, latencies shortened for both types of responses, but at different time courses. The former from about 25 ms preoperatively, to about 20 ms.

Table 3. Neurophysiologic Assessments of (i) Cortical Excitability Assessed by nTMS and (ii) Degree of Splitting of Motor Responses Elicited by nTMS and Nerve Stimulation at the Wrist Level, Respectively

		Pre Nerve Transfer		3 Months Post Nerve Transfer		12 Months Post Nerve Transfer	
		APB*	ADM†	APB*	ADM†	APB*	ADM†
Cortical excitability	RMT‡ (V/m)	85/87	78/67	81/82	91/76	78/79	75/84
	Response amplitude at RMT‡ (μV)	267/NA	98/148	101/465	1422/NA	221/101	1291/220
	SR§ (μV)	NA/74, NA, 231	66, 98, 98/69, 104, 147	101, 878, 988/NA, NA, 465	692, 1169, 1421/ NA, NA, 366	221, 488, 1030/101, 255, 1024	292, 706, 1291/220, 486, 1135
Splitting of motor responses	nTMS (arbitrary units)	0/1	2/2	0/2	1/2	2/3	1/3
	ENG (arbitrary units)	0/0	1/0	0/0	0/1¶	0/0	0/0‖

*Abductor pollicis brevis muscle.
†ADM muscle.
‡Resting motor thresholds.
§Stimulus response.
¶3 units when stimulated below the elbow.
‖1 unit when stimulated below the elbow (for explanation of arbitrary units and splitting of responses, see text).
For each parameter, results are given as Patient 1/Patient 2. NA; not available/applicable.

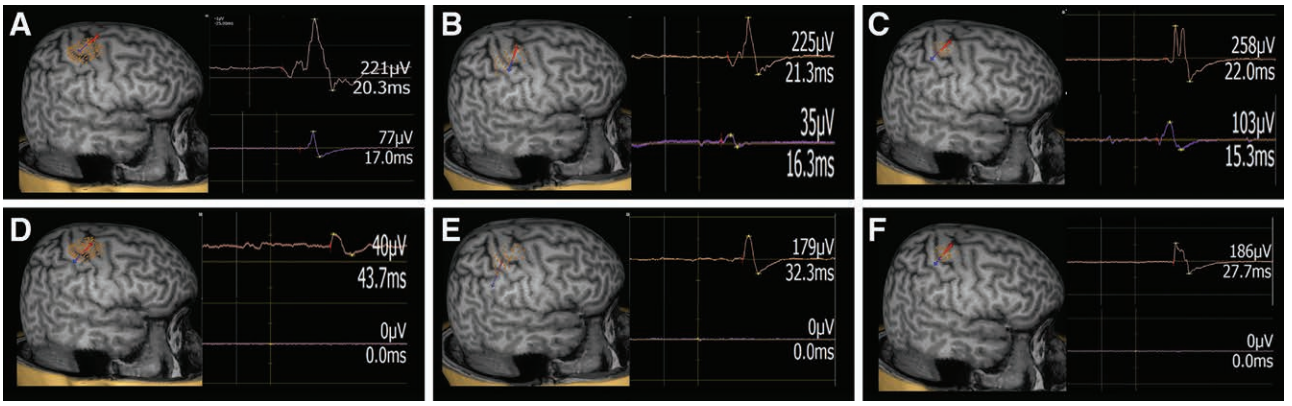

Fig. 3. Two populations of peripheral muscle responses. Representative muscle responses (first patient) from the ADM (orange traces) and flexor carpi ulnaris (purple traces), respectively. Double-pointed arrows indicate location and direction of stimulation, and digits indicate response amplitudes and latencies. A–C, Right column with early responses. D–F, Right column with late responses from the ADM. A, D, Preoperatively. B, E, From 3 months post nerve transfer. C, F, From 12 months post nerve transfer.

The latter demonstrated a larger change: appoximately 40-, 30-, and 25 ms at the three points, respectively. Simultaneous recording from the flexor carpi ulnaris muscle produced responses that were generally seen in parallel to short-, but not to long latency responses in the ADM muscle.

Over the time of observation, there was a movement of the "hot-spot" (the location in primary motor cortex with maximal excitability) for the ADM muscle in anterior-posterior direction (Fig. 4) and change in the cortical area of activation for the same muscle (Fig. 5).

DISCUSSION

In this study, we confirm improved functional outcome with a low complication rate, following end-to-side nerve transfer of the AIN to the motor branch of the ulnar nerve in two patients with an earlier repaired proximal ulnar nerve injury. We used a broad spectrum of methods to show both peripheral and central neuroplasticity.

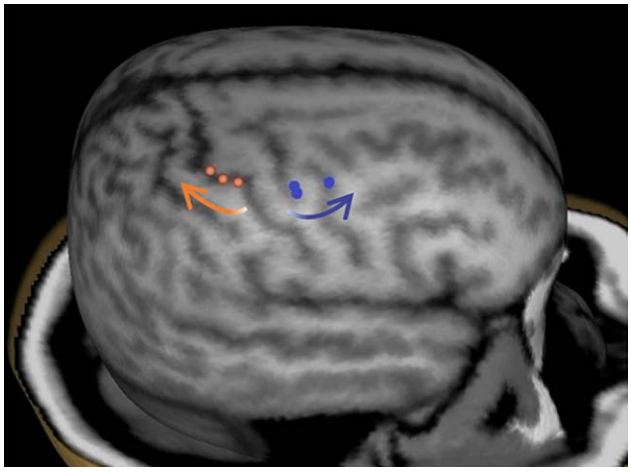

Fig. 4. Movement of hot-spot in anterior-posterior direction. Localization of the optimal point of activation of the ADM muscle at the three time points studied for the two patients (orange and blue markers for the first and second patient, respectively). The locations of the markers were transferred to a general brain volume for demonstration purposes. Therefore, the absolute localization in relation to the anatomy cannot be decided from this image.

Improved muscle function was probably due to plastic processes at many levels.[19–22,32] Regarding the cortical level at least three findings indicate plastic changes. At the time of the AIN transfer, both patients were in a stable chronic phase after the nerve injury. Therefore, the demonstrated changes were by all probability induced by the said transfer. Firstly, for both patients, there was a movement of the hotspot for the ADM muscle of 8–10 mm, compared with the test–retest variability of about 2–3 mm.[27] Secondly, the size of the area from where responses could be elicited in the ADM muscle changed over time, and thirdly, a second population of responses with long latency was detected. Interestingly, the hot-spot moved posteriorly in the first patient and anteriorly in the second one.

Complete motor reinnervation of the investigated intrinsic hand muscles was shown with ENG, EMG, and nTMS over a period of 12 months. As we found split motor unit potentials for the ADM muscle when stimulating the median nerve at the elbow, we consider the reinnervation to at least partly come from median nerve fibers. This was presumably due to slower conduction in the new motor pathways formed by the side-to-end anastomosis.

Both patients reported improved hand function (Table 1) and returned to normal activity, such as full-time work as hairdresser and carpenter, respectively (data not shown). The result from the DASH, EQ-5D, and VAS current health status questionnaires, however, did not mirror the improved hand function, probably due to the complexity with many other aspects of life affecting these scores.

The AIN nerve transfer has been described to not induce weakness of the pronation postoperatively, as the function of the PT muscle is sufficient to uphold pronation.[13] However, the first patient in our study lost strength and range of motion following the nerve transfer, probably due to prior direct damage to the PT muscle caused by the fractures of the forearm, but he recovered to almost normal function over time. There

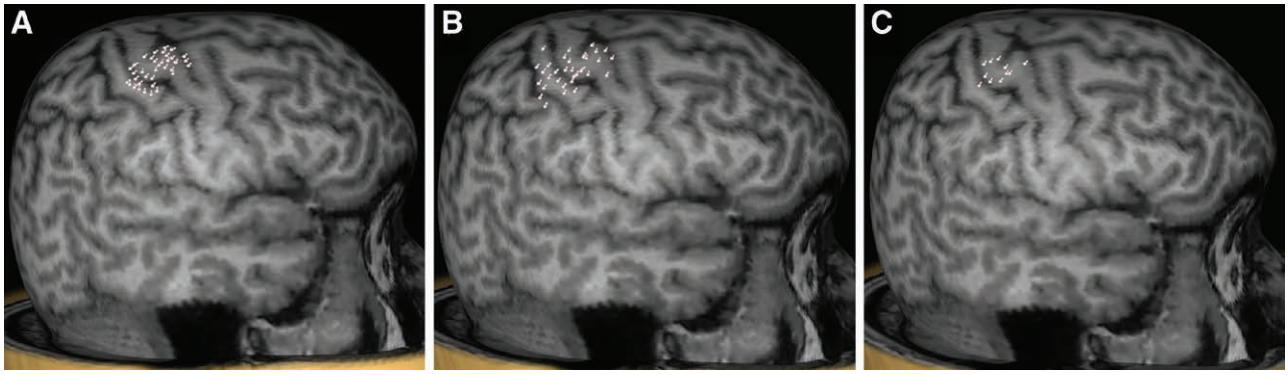

Fig. 5. The cortical area of activation for the ADM muscle. The area could, for technical reasons, only be evaluated for the first patient. Stimulation points (white markers) at the three time points: Pre nerve transfer (A), 3 months post nerve transfer (B), and 12 months post nerve transfer (C) of testing where stimulation elicited a response in the ADM muscle larger than 50 μV. Stimulation was performed at the resting motor threshold of the respective time point. The location did not change appreciably over the period of observation. The area, however, tended to be large preoperatively, increase further at 3- to shrink below the initial level at 12 months postoperatively.

were surprising findings regarding the PQ muscle, believed to be surgically completely denervated by the nerve transfer. This might be explained by the procedure leaving a very proximal branch from the AIN, that is also the thickest,[12] to the PQ muscle that completely reinnervated the muscle.

When comparing the total Rosen score for our patients with the estimated predicted values after nerve repair at the wrist level, a "leap" of the curve is seen. Thus, the AIN transfer places these proximal injuries within the outcome interval for a nerve injury at the wrist level. Analyzing specifically the manual muscle testing according to the MRC system,[33] adduction of the fifth finger did not improve as much as adduction for the second and fifth fingers three years after the AIN nerve transfer (data not shown), the first patient still had not achieved any adduction of the fifth finger and had complementary surgery with a tendon transfer. Our personal experience (EN and CR) is that adduction of the fifth finger is weak after most ulnar nerve injuries. Maybe it is due to the small size or nerve composition, affecting axonal regeneration into the third volar interosseus muscle, responsible for adduction of the fifth finger. A similar phenomenon was seen in animal studies where injury to the sciatic nerve resulted in longer axonal outgrowth in the thicker tibial nerve than in the thinner peroneal nerve.[34]

The patients in the present study were the first to receive the AIN nerve transfer at our unit and even though having the nerve transfer late after the initial nerve injury, the results were encouraging. We suggest that patients with a proximal ulnar nerve injury should have surgery with the AIN transfer, preferably as early as possible after the nerve is harmed. Our intention was to study regeneration and outcome of the AIN to the ulnar motor branch transfer and, more importantly, evaluate neuromuscular plasticity. To our knowledge this has not been described earlier. We conclude that the AIN to ulnar motor branch nerve transfer improves the intrinsic motor function of the hand following a proximal ulnar nerve injury and that several plastic mechanisms are involved. Surprisingly, we can also report an almost complete reinnervation of the PQ muscle. In conclusion, although based on two cases, we consider our data as new and valuable to other hand and nerve surgeons treating these conditions.

Erika Nyman, MD, PhD
Department of Hand Surgery, Plastic Surgery and Burns and
Department of Biomedical and Clinical Sciences
Linköping University, S-581 85
Linköping, Sweden
E-mail: erika.nyman@liu.se

ACKNOWLEDGMENTS

The authors thank Oumie Thorell, Madeleine Winberg, and Linda Borén for their excellent help and support regarding patient examinations and rehabilitation.

REFERENCES

1. Vordemvenne T, Langer M, Ochman S, et al. Long-term results after primary microsurgical repair of ulnar and median nerve injuries. A comparison of common score systems. *Clin Neurol Neurosurg.* 2007;109:263–271.
2. Rosén B, Lundborg G. The long term recovery curve in adults after median or ulnar nerve repair: a reference interval. *J Hand Surg Br.* 2001;26:196–200.
3. Murovic JA. Upper-extremity peripheral nerve injuries: a Louisiana State University Health Sciences Center literature review with comparison of the operative outcomes of 1837 Louisiana State University Health Sciences Center median, radial, and ulnar nerve lesions. *Neurosurgery.* 2009;65(4 suppl):A11–A17.
4. Woo A, Bakri K, Moran SL. Management of ulnar nerve injuries. *J Hand Surg Am.* 2015;40:173–181.
5. Gaul JS Jr. Intrinsic motor recovery—a long-term study of ulnar nerve repair. *J Hand Surg Am.* 1982;7:502–508.
6. Roganovic Z. Missile-caused ulnar nerve injuries: outcomes of 128 repairs. *Neurosurgery.* 2004;55:1120–1129.
7. Ehni BL. Treatment of traumatic peripheral nerve injury. *Am Fam Physician.* 1991;43:897–905.
8. Tung TH, Mackinnon SE. Nerve transfers: indications, techniques, and outcomes. *J Hand Surg Am.* 2010;35:332–341.
9. Rinker B. Nerve transfers in the upper extremity: a practical user's guide. *Ann Plast Surg.* 2015;74(suppl 4):S222–S228.

10. Wang Y, Zhu S. Transfer of a branch of the anterior interosseus nerve to the motor branch of the median nerve and ulnar nerve. *Chin Med J (Engl).* 1997;110:216–219.
11. Battiston B, Lanzetta M. Reconstruction of high ulnar nerve lesions by distal double median to ulnar nerve transfer. *J Hand Surg Am.* 1999;24:1185–1191.
12. Novak CB, Mackinnon SE. Distal anterior interosseous nerve transfer to the deep motor branch of the ulnar nerve for reconstruction of high ulnar nerve injuries. *J Reconstr Microsurg.* 2002;18:459–464.
13. Davidge KM, Yee A, Moore AM, et al. The supercharge end-to-side anterior interosseous-to-ulnar motor nerve transfer for restoring intrinsic function: clinical experience. *Plast Reconstr Surg.* 2015;136:344e–352e.
14. Dunn JC, Gonzalez GA, Fernandez I, et al. Supercharge end-to-side nerve transfer: systematic review. *Hand (N Y).* 2021;16:151–156.
15. Baltzer H, Woo A, Oh C, et al. Comparison of ulnar intrinsic function following supercharge end-to-side anterior interosseous-to-ulnar motor nerve transfer: a Matched Cohort Study of Proximal Ulnar Nerve Injury Patients. *Plast Reconstr Surg.* 2016;138:1264–1272.
16. Farber SJ, Glaus SW, Moore AM, et al. Supercharge nerve transfer to enhance motor recovery: a laboratory study. *J Hand Surg Am.* 2013;38:466–477.
17. Bontioti E, Dahlin LB, Kataoka K, et al. End-to-side nerve repair induces nuclear translocation of activating transcription factor 3. *Scand J Plast Reconstr Surg Hand Surg.* 2006;40:321–328.
18. Koriem E, El-Mahy MM, Atiyya AN, et al. Comparison between supercharged ulnar nerve repair by anterior interosseous nerve transfer and isolated ulnar nerve repair in proximal ulnar nerve injuries. *J Hand Surg Am.* 2020;45:104–110.
19. Fornander L, Nyman T, Hansson T, et al. Inter-hemispheric plasticity in patients with median nerve injury. *Neurosci Lett.* 2016;628:59–66.
20. Taylor KS, Anastakis DJ, Davis KD. Cutting your nerve changes your brain. *Brain.* 2009;132(pt 11):3122–3133.
21. Yu A, Wang S, Cheng X, et al. Functional connectivity of motor cortical network in patients with brachial plexus avulsion injury after contralateral cervical nerve transfer: a resting-state fMRI study. *Neuroradiology.* 2017;59:247–253.
22. Stephenson JB IV, Li R, Yan JG, et al. Transhemispheric cortical plasticity following contralateral C7 nerve transfer: a rat functional magnetic resonance imaging survival study. *J Hand Surg Am.* 2013;38:478–487.
23. Mohanty CB, Bhat D, Devi BI. Role of central plasticity in the outcome of peripheral nerve regeneration. *Neurosurgery.* 2015;77:418–423.
24. Anastakis DJ, Malessy MJ, Chen R, et al. Cortical plasticity following nerve transfer in the upper extremity. *Hand Clin.* 2008;24:425–444, vi.
25. Li T, Hua XY, Zheng MX, et al. Different cerebral plasticity of intrinsic and extrinsic hand muscles after peripheral neurotization in a patient with brachial plexus injury: a TMS and fMRI study. *Neurosci Lett.* 2015;604:140–144.
26. Rossini PM, Di Iorio R, Bentivoglio M, et al. Methods for analysis of brain connectivity: an IFCN-sponsored review. *Clin Neurophysiol.* 2019;130:1833–1858.
27. Ilmoniemi RJ, Ruohonen J, Karhu J. Transcranial magnetic stimulation—a new tool for functional imaging of the brain. *Crit Rev Biomed Eng.* 1999;27:241–284.
28. Atroshi I, Gummesson C, Andersson B, et al. The disabilities of the arm, shoulder and hand (DASH) outcome questionnaire: reliability and validity of the Swedish version evaluated in 176 patients. *Acta Orthop Scand.* 2000;71:613–618.
29. Burström K, Sun S, Gerdtham UG, et al. Swedish experience-based value sets for EQ-5D health states. *Qual Life Res.* 2014;23:431–442.
30. Rosén B, Lundborg G. A model instrument for the documentation of outcome after nerve repair. *J Hand Surg Am.* 2000;25:535–543.
31. Thordstein M, Saar K, Pegenius G, et al. Individual effects of varying stimulation intensity and response criteria on area of activation for different muscles in humans. A study using navigated transcranial magnetic stimulation. *Brain Stimul.* 2013;6:49–53.
32. Thordstein M, Hallböök T, Lundgren J, et al. Transfer of cortical motor representation after a perinatal cerebral insult. *Pediatr Neurol.* 2011;44:131–134.
33. Brandsma JW, Schreuders TA, Birke JA, et al. Manual muscle strength testing: intraobserver and interobserver reliabilities for the intrinsic muscles of the hand. *J Hand Ther.* 1995;8:185–190.
34. Dahlin LB, Miyauchi A, Thomsen P, et al. Stimulation of nerve regeneration by macrophages in granulation tissue. *Restor Neurol Neurosci.* 1996;9:141–149.