Rectus Abdominis Motor Nerves as Donor Option for Free Functional Muscle Transfer: A Cadaver Study and Case Series

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Abstract

Background: Current management of brachial plexus injuries includes nerve grafts and nerve transfers. However, in cases of late presentation or pan plexus injuries, free functional muscle transfers are an option to restore function. The purpose of our study was to describe and evaluate the rectus abdominis motor nerves histomorphologically and functionally as a donor nerve option for free functional muscle transfer for the reconstruction of brachial plexus injuries. **Methods:** High intercostal, rectus abdominis, thoracodorsal, and medial pectoral nerves were harvested for histomorphometric analysis from 4 cadavers from levels T3-8. A retrospective chart review was performed of all free functional muscle transfers from 2001 to 2014 by a single surgeon. **Results:** Rectus abdominis nerve branches provide a significant quantity of motor axons compared with high intercostal nerves and are comparable to the anterior branch of the thoracodorsal nerve and medial pectoral nerve branches. Clinically, the average recovery of elbow flexion was comparable to conventional donors for 2-stage muscle transfer. **Conclusion:** Rectus abdominis motor nerves have similar nerve counts to thoracodorsal, medial pectoral nerves, and significantly more than high intercostal nerves alone. The use of rectus abdominis motor nerve branches allows restoration of elbow flexion comparable to other standard donors. In cases where multiple high intercostal nerves are not available as donors (rib fractures, phrenic nerve injury), rectus abdominis nerves provide a potential option for motor reconstruction without adversely affecting respiration.

Keywords: free functional muscle transfer, brachial plexus injury, nerve transfer, rectus abdominis nerves, intercostal nerves

Introduction

Current management of complete plexus injuries most commonly requires use of intercostal nerves (ICNs) for nerve transfer and/or to motor a free functional muscle transfer (FFMT) depending on the timing of reconstruction. Even with early nerve transfers, FFMT is used for hand function as the finger flexors are too distant for successful nerve transfer.^{4,11,14} The literature supports an outcome of medical research council (MRC) grades of 3 or better for FFMT.^{1,4,6,9} Many extraplexal nerves have been described to power a FFMT. The most commonly used donors are high ICNs (T3-6), spinal accessory nerve (SAN), or contralateral C7.⁶ However, the SAN is usually used to restore or maintain shoulder stability. The contralateral C7 has shown efficacy by some but is also associated with donor site morbidity, and motor reeducation is more complicated.^{2,7,12} Unfortunately,

because of the traumatic nature of most brachial plexus injuries, rib fractures and phrenic nerve injuries are common. In these patients, use of multiple high ICNs in the presence of a phrenic nerve injury has the potential to downgrade respiratory function and may result in subjective shortness of breath.³ If there are multiple rib fractures, the corresponding ICNs may also not be functional for use as a nerve transfer. As rib fractures in brachial plexus injuries often involve high and middle level ribs, the lower level ribs that also supply

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the innervation to the rectus abdominis (T7-12) are often spared.

There are several case scenarios for use of the ICNs, and especially the lower ICNs and their rectus abdominis branches, as donor nerves. Patients who present or are referred within 8 to 10 months of injury are candidates for nerve transfers, usually consisting of high ICN (T3-6) transfer to the musculocutaneous nerve for elbow flexion, and distal SAN to the suprascapular nerve for shoulder function. No other donor nerve options then exist in close proximity for a single-stage FFMT for hand function. In these cases, we use the rectus abdominis branches of the low ICNs (T7-8) to reinnervate or “bank” a sural nerve graft as the first stage for a FFMT for finger flexion or to augment weak elbow flexion from the nerve transfer in the future once the regenerating axons have reached the distal end of the nerve graft as they are too distant for a single-stage muscle transfer.

For patients who present or are referred 10 to 12 months or more after injury, nerve transfers will not be successful, and therefore FFMT is recommended. If high ICNs are available (ie, no rib fractures, phrenic nerve intact, and no nerve transfer previously attempted), they can be used to motor a FFMT often in 1 stage. If the high ICNs are not available for the previously listed reasons, then low ICNs with their rectus abdominis branches can be used for a 2-stage FFMT. Even if the phrenic nerve is not functional, the rectus abdominis branches can still be used as they have less effect on respiration than the high ICNs. Occasionally, the thoracodorsal or medial pectoral nerves may recover after a year or two and then become available as a donor motor nerve for a single-stage FFMT where they were not functional initially for use as a nerve transfer.

The rectus abdominis motor nerve branches arise from the anterior rami of the T7-12 spinal nerves traveling with their respective ICNs between the transverse abdominis and the internal oblique muscles. The rectus abdominis nerves split from the intercostal branches and penetrate the lateral rectus sheath to segmentally supply the rectus abdominis muscle. The rectus abdominis nerves can reliably be found at the T7 intercostal space or lower.^{5,10}

The purpose of our study was to evaluate and compare the rectus abdominis motor nerves as a donor nerve option for FFMT in the reconstruction of brachial plexus injuries. In this study, we performed both cadaveric dissections and a case series to compare the rectus abdominis nerves to other standard donor nerves.

Cadaver Dissection

Materials and Methods

Four human cadavers were dissected at ICN levels T3-8 from the midaxillary to the midclavicular line (Figure 1). Intercostal nerve specimens were harvested at the midaxillary line, anterior axillary line, and midclavicular line bilaterally. We

Figure 1. Cadaver dissection at levels T5-8 demonstrating intercostal nerves at T5-6 and much larger rectus abdominis nerves at T7-8.

harvested the thoracodorsal and medial pectoral nerves from 2 cadavers. The nerves were fixed in 3% glutaraldehyde solution (Polysciences Inc, Warrington, Pennsylvania) in 0.1 M phosphate buffer (pH 7.2) at 4°C prior to sectioning and histomorphological analysis. We then postfixated the tissues with 1% osmium tetroxide and serially dehydrated in ethanol. Specimens were embedded in Araldite 502 (Polysciences) and sectioned into 1- μ m thick cross-sections using a LKB Broma 8800 Ultratome III microtome (LKB Instruments, Mt Waverley, Victoria). We stained the sections with 1% toluidine blue and evaluated via light microscopy.⁸ A blinded observer evaluated the slides for overall nerve architecture and quantity of regenerated nerve fibers.

Results

The average nerve counts for lower intercostal + rectus abdominis (T7-8) at the midaxillary, anterior axillary, and midclavicular line were 5470 (± 3357), 4699 (± 2538), and 2465 (± 774) (Figure 2). For higher ICNs (T3-6), the average nerve counts at the midaxillary, anterior axillary, and midclavicular line were 3329 (± 1653), 2055 (± 1109), and 1872 (± 664), respectively. The average nerve count for medial pectoral nerves and anterior branch of the thoracodorsal nerve was 2718 (± 638) and 3209 (± 2327), respectively. Comparing ICN + rectus versus ICN counts, we found a significant difference at the anterior axillary line

Figure 2. Total axon number of intercostal/rectus abdominis nerve based on location.
 Note. Error bars are measures of standard error of the mean. ICN = intercostal nerve.

and total nerve count ($P = .002$, 95% confidence interval [CI] $[-4211$ to $-1077]$ and $P = .0009$ 95% CI $[-2876.4$ to $-783.6]$, respectively); however, it was not significant at the midaxillary line or midclavicular line ($P = .0884$ 95% CI $[-4642.7$ to $360.7]$ and $P = .138$ 95% CI $[-1396.3$ to $210.3]$, respectively).

Case Series

Materials and Methods

Over a 13-year period (2001-2014), we identified all patients who had undergone FFMT to the upper extremity. With institutional review board approval, we reviewed charts for age, gender, handedness, mechanism of injury, nerve donor, graft source, graft length, time to second-stage surgery, pre- and postoperative MRC grade, follow-up duration, and additional procedures. Our inclusion criteria were: (1) preoperative elbow flexion of MRC grade 0 or 1, (2) FFMT for elbow flexion, (3) single donor, and (4) patients who had follow-up time of at least 2 years. MRC grade for elbow flexion was determined by the senior author at routine follow-up visits and was based on the modified MRC grading system. Statistical analysis of histomorphometric data was performed using the Student t test.

Patient Selection

For the patients who presented within a time frame for nerve transfer as described previously, in the first stage we performed high ICN (T3-6) transfers to the musculocutaneous nerve and banked a sural or medial antebrachial cutaneous (MABC) nerve graft coapted to the lower ICNs (T7-8) with their respective rectus abdominis motor nerves in the subcutaneous space from the chest to the arm (Figure 3). We marked the distal graft with blue polypropylene suture

Figure 3. Rib dissection of left chest illustrating size difference of upper intercostal nerve at T3 (black arrowhead) and the lower rectus abdominis nerves at T7-8 (white arrowheads).

to facilitate identification in the second-stage FFMT. We followed up patients with an advancing Tinel sign to follow nerve regeneration through the graft. In patients who presented outside the range in which nerve transfers would be feasible, we used the high ICNs if available or the lower ICNs with their associated rectus abdominis nerves to bank a long nerve graft to motor a FFMT at a second stage. We selected a variety of FFMT cases motored by different donor nerve including the rectus abdominis branches to allow comparison of outcomes.

Operative Technique

Gracilis harvest. The gracilis muscle was harvested from the contralateral side to facilitate a 2-team approach. The obturator nerve branch was dissected for maximum length. Two

Figure 4. Gracilis muscle harvest from the left medial thigh.

separate distal incisions were made at the medial distal thigh and at the insertion of the gracilis to the pes anserinus below the knee in order to obtain the maximal tendon length (Figure 4).

ICN and rectus abdominis nerve harvest. Harvest of the high ICNs has been well described. Briefly, subperiosteal dissection exposed the inferior half of the rib and dissection of the intercostal muscle at its border with the superior rib exposed the intercostal neurovascular bundle. The nerve was found just deep to the vessels and verified by electrical stimulation. High ICNs are long and small, and were dissected anteriorly for maximal length. Low ICNs and their rectus abdominis motor branches were found and dissected in the same manner, but the rectus abdominis branches were notably larger than intercostal branches and also easily verified by contraction of the rectus abdominis muscle (Figure 3).

Insetting. We used previous medial incisions in the arm along the brachial sulcus extending in a zigzag fashion across the anterior axillary fold. We identified the donor nerve graft previously marked by blue polypropylene suture for those individuals who had banked sural nerve grafts to ICNs or the SAN. The nerve graft was serially transected and inspected for fascicles to insure a good-quality donor. We then isolated branches of the brachial artery and vein for donor blood supply. A longitudinal incision was made in the volar forearm, and the flexor digitorum profundus (FDP) and flexor pollicis longus (FPL) tendons were identified. The gracilis muscle was then harvested and moved to the arm where arterial and venous anastomoses and nerve coaptations were performed to the brachial vessel branches and banked nerve graft, respectively. For ICN and SAN nerve donors, the deltopectoral groove was dissected to expose the superior humerus. Bone anchors were inserted in the humerus, and FiberWire suture was used to secure the proximal muscle which was reinforced with a gastrointestinal anastomosis stapler. The distal muscle was then passed through a tunnel under the antebrachial fascia and lacertus

Figure 5. Just prior to inseting of muscle transfer using the lacertus fibrosis as a pulley at the elbow, and flexor digitorum profundus and flexor pollicis longus tendons for distal suture site.

fibrosis as a pulley and sutured to the FDP and FPL in a Pulvertaft weave fashion to provide some finger flexion/tension as well (Figure 5).

For those patients who had thoracodorsal donor nerves, an incision was made along the lateral chest wall to identify the latissimus muscle and the thoracodorsal neurovascular pedicle on its deep surface. The gracilis was then anchored proximally to the clavicle and distally to the biceps tendon by a Pulvertaft weave. A similar inseting procedure was used for medial pectoral donors after isolating the medial pectoral nerve branches beneath the pectoralis major and minor muscles.

All patients postoperatively were monitored closely in the hospital for an average of 5.2 (± 1.3) days. They were placed in a shoulder immobilizer maintaining elbow flexion of at least 90° to protect the proximal and distal attachments. Hand therapists evaluated and followed up the patients for range-of-motion exercises initially and then motor reeducation.

Results

We identified 17 patients who met our inclusion criteria (Table 1). Fifteen patients were male, and 2 were female. The median age was 28.5 (quartiles: 24.3, 42.3). The mechanism of injury was predominately motor vehicle collisions (5) or motor cycle collisions (6), followed by ATV accidents (3), direct shoulder trauma (2), and a 37-foot fall (1). The median time between first stage and second stage reconstruction was 18 months (quartiles: 12, 26). The nerve donor was the SAN in 5 patients, ICN + rectus in 3 patients, rectus abdominis nerves in 3 patients, medial pectoral nerve in 2 patients, ICN alone in 1 patient, and the thoracodorsal nerve in 1 patient. The MABC nerve was the most common nerve graft (7), followed by the sural nerve (5) in the ICN and distal SAN groups with average length of 22.8 ± 5.8 cm. The median follow-up time was 25 months (quartiles: 21.5, 35).

The average recovery of elbow flexion was MRC grade 3/5 for ICN nerve alone (1 patient), 3.3/5 for ICN + rectus abdominis nerves (5 patients), and 2.6/5 for distal SAN (5

Table 1. Patient Information.

Patient No.	Age/sex	Injury mechanism	Injury	Time to FFMT (mo)	Donor nerve	Follow-up duration (mo)	Outcome (MRC)
1	23 / M	MCC	Complete	9	Distal SAN	11	M3
2	29 / F	MVC	C7-C8 avulsion	8	ICN + rectus abdominis	84	M4
3	23 / M	MCC	Complete	28	Distal SAN	25	M4
4	63 / M	ATV	Complete	18	Distal SAN	23	M2
5	31 / M	MCC	Complete	25	ICN × 3	21	M3
6	29 / M	MVC	C6-C7 avulsion	65	Distal SAN	57	M3
7	25 / M	MCC	C5-C8	15	MPN	39	M5
8	21 / F	MVC	C5-C6 avulsion	60	FCU fascicle of ulnar nerve	11	M2
9	24 / M	Football trauma	C5-C8 avulsion	8	ICN + rectus abdominis	27	M4
10	52 / M	37 ft fall	C5-C6	35	MPN	12	M4
11	46 / M	MCC	C5-C6 avulsion	11	Thoracodorsal	42	M4
12	26 / M	MVC	Complete	39	ICN + rectus abdominis	38	M2
13	53 / M	MVC	Complete	56	Rectus abdominis	22	M3
14	70 / M	Blunt injury to shoulder	Complete	17	Distal SAN	34	M3
15	34 / M	MCC	C5-C6 avulsion	47	MPN	20	M3
16	20 / M	ATV	Complete	24	Rectus abdominis	27	M3
17	55 / M	ATV	C5-C7	31	Rectus abdominis	23	M3

Note. FFMT = free functional muscle transfer; MRC = medical research council; SAN = spinal accessory nerve; ICN = intercostal nerves; MCC = motorcycle crash; MVC = motor vehicle crash; ATV = All-terrain vehicle crash; MPN = medial pectoral nerve; FCU = flexor carpi ulnaris.

patients). Each of these required 2 stages with a nerve graft. Average postoperative elbow flexion for medial pectoral nerve donors was 4/5 (2 patients) and for anterior branch of thoracodorsal nerve was 4/5 (1 patient). These were single-stage operations without nerve grafts. We obtained MRC grade ≥ 3 in 80% of ICN + rectus group.

There were no flap failures. There were also no abdominal wall complications (bulging, hernia, weakness) observed. One patient required a return to the operating room for reexploration for concern of flap compromise however was found to have intact blood supply. One patient required an additional tenolysis procedure. One patient eventually required distal forearm amputation 5 years after FFMT secondary to an unrelated infectious event.

Discussion

Complete brachial plexus injuries represent a challenge to reconstructive surgeons as donor nerve options are limited. Available donor motor nerves may include the ICNs, SAN, thoracodorsal nerve, or medial pectoral nerve to power FFMTs. In this study, we performed a histomorphometric analysis and review of our experience with the use of the rectus abdominis nerves for donors in FFMT. We have shown that the nerve counts are equivalent or larger than other standard donor nerves, and the functional results are comparable. The rectus nerves are routinely found as branches of the lower ICNs.⁵ They are visibly larger on dissection and have a greater number of nerve fascicles.

Intraoperative nerve stimulation easily confirms the rectus abdominis innervation. There is no donor site morbidity as we only harvest the upper rectus branches, and the other lower segmental rectus branches remain intact.

We present a series of patients treated with a new technique for patients with very limited reconstructive options. We lost several patients to follow-up due to the distance many patients travel to our center. We felt that complete recovery of muscle strength is best ascertained at least 18 months after the FFMT, and many patients were lost to follow-up after this time point. It is difficult in this series to differentiate the contributions from the rectus abdominis motor nerves and the intercostal muscle branches of the lower ICNs. However, the rectus abdominis donors do provide more substantial motor fascicles based on our histomorphometric analysis, and we feel they are the major contributors to reinnervating the FFMT. Because they are larger and provide more motor axons, dissection of fewer rib levels (usually only 1 or 2) is usually sufficient to provide a satisfactory quantity of donor axons.

Their harvest is straightforward and uses the same technique for high ICNs. As they are located low on the rib cage, a nerve graft is required to reach the arm, and their use is therefore ideal for the first stage in a 2-stage FFMT reconstruction. Their length is similar to the high ICNs if dissected medially to the rectus abdominis muscle, but we limit this dissection as a nerve graft will already be required and to leave the abdominal fascia intact. These larger nerves may also make up for the longer nerve grafts and distance

of recovery when compared with upper ICN donors. In addition, cortical reeducation of rectus abdominis donor nerves may be easier than ICNs as the rectus abdominis muscle is under more volitional control. Medial pectoral or thoracodorsal nerve branches are preferred if available as they allow muscle transfer in one stage, are more easily rehabilitated, and achieve better results.

Considering that most patients have sustained multiple injuries that may include rib fractures, high ICNs may not be functional. Subsequent harvest of the phrenic nerve in such cases can decrease respiratory drive and lead to subjective shortness of breath.^{3,13} Chuang et al³ showed mild dyspnea in 8 out of 20 patients up to 6 months after phrenic plus ICN transfer. Zheng et al¹³ showed all their patients had some exertional dyspnea with moderate exercise, but they did not further subdivide their patients. In addition, 7 of 42 patients experienced medium dyspnea with vigorous exercise. Chuang et al³ showed a statistically significant decrease in measurable lung function in patients undergoing phrenic plus ICN transfers as compared with phrenic nerve or ICN transfers alone. This subjective finding has been similar to our own experience with use of the high ICNs in patients with concomitant phrenic nerve injuries. If the phrenic nerve is not functional, then harvest of multiple high ICNs will similarly lead to respiratory compromise and is not recommended. For such cases, we advocate use of rectus abdominis nerve donors at T7-8 levels for a 2-staged muscle transfer without adversely affecting respiration.

Many authors have previously published FFMT with ICN alone donors with reported MRC grade 3 outcomes in 68% to 83% of their patient population.⁶ In this series, we have shown MRC grades of 3 or better in 80% of our ICN + rectus group. In addition, we have experienced no donor site morbidity. We believe the rectus abdominis motor nerves provide another donor option for patients with devastating brachial plexus injuries, and especially in complete injuries where donor availability is further limited by rib fractures or phrenic nerve involvement.

Ethical Approval

This study was approved by our institutional review board.

Statement of Human and Animal Rights

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008.

Statement of Informed Consent

Informed consent was obtained from all individual participants included in this study.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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