Outcomes of surgery in 1019 brachial plexus lesions treated at Louisiana State University Health Sciences Center

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Object. Outcomes of 1019 brachial plexus lesions in patients who underwent surgery at Louisiana State University Health Sciences Center during a 30-year period are reviewed in this paper to provide management guidelines.

Methods. Causes of brachial plexus lesions included 509 stretches/contusions (50%), 161 plexus tumors (16%), 160 thoracic outlet syndromes (TOSs, 16%), 118 gunshot wounds (12%), and 71 lacerations (7%). Many features of clinical presentation, including prior treatment, patient’s neurological status, results of electrophysiological studies, intraoperative findings, and postoperative level of function, were studied. The minimum follow-up period was 18 months and the mean follow-up period was 42 months. Repairs were best for injuries located at the C-5, C-6, and C-7 levels, the upper and middle trunk, the lateral cord to the musculocutaneous nerve, and the median and posterior cords to the axillary and radial nerves. Conversely, results were poor for injuries at the C-8 and T-1 levels, and for lower trunk and medial cord lesions, with the exception of injuries of the medial cord to the median nerve. Outcomes were most favorable when patients were carefully evaluated and selected for surgery, although variables such as lesion type, location, and severity, as well as time since injury also affected outcome. This was true also of TOSs and tumors arising from the plexus, especially if they had not been surgically treated previously.

Conclusions. Surgical exploration and repair of brachial plexus lesions is technically feasible and favorable outcomes can be achieved if patients are thoroughly evaluated and appropriately selected.

KEY WORDS • brachial plexus injury • thoracic outlet syndrome • nerve sheath tumor • nerve graft • nerve action potential

Clinical Material and Methods

Patient Population

Between 1968 and 1998, approximately 2500 patients with brachial plexus lesions were evaluated at LSUHSC. One thousand nineteen lesions were selected for surgery. Patients were referred primarily from the southern and midwestern portions of the US, although patients from other regions and other countries were also seen. The patients ranged in age from 4 to 73 years, with a median age of 34 years. Each patient’s sex and neurological status, the type of injury, its presentation, and its prior treatment were recorded. Electrophysiological studies were also conducted preoperatively. Details of the surgical procedure used at LSUHSC, intraoperative electrophysiological and pathological findings, and postoperative functional status were recorded. The minimum follow-up period was 18 months with a mean follow-up period of 42 months.

Categorization of Injuries

Mechanisms of brachial plexus injuries included 509 stretches/contusions (50%), many of which had avulsions; 161 nerve sheath tumors (16%); 160 suspected TOSs (16%); 118 GSWs (12%); and 71 lacerations (7%) (Table
1). Patients suffering from birth palsy were excluded from this study, as were patients with nonnerve sheath tumors or tumors of intraspinal origin. Tumors located on the plexus or on the intraforaminal root or extratubinal spinal nerve, however, were included. Iatrogenic lesions (30 cases) were included in either the stretch/contusion or laceration groups.

Grading Neural Function

Preoperative neural function was graded for each individual plexus element, and then the grades were combined for the elements involved (Table 2).29,30 This LSUHSC grading system was used to give more extensive functional recovery classifications than the British Medical Research Council system,45,47 as well as a more precise method for evaluating both proximal and distal recovery of motor function.

Postoperative recovery grades (range 0–5) for the various patterns of brachial plexus injuries or tumors were calculated for each element and were aggregated and averaged to obtain the overall grade. Successful outcomes were defined as Grade 3 or higher. Good and excellent recoveries were represented by Grades 4 and 5, respectively. If an element was considered irreparable and no attempt was made to lead outflow from the proximal portion or to neurotize it, it was excluded from the calculations. Irreparable situations usually corresponded with C8–T1 roots or lower trunk elements; therefore, some grades applied to the supraclavicular flap arm series reflect averaged grades for muscles at C-5, C-6, and C-7 only. Despite this, the data still reflect the difficulties encountered in restoring neural function to patients with flap arms.

Each clinical assessment was augmented by radiological and electrodiagnostic studies. More than 95% of the patients had undergone preoperative nerve conduction studies and EMG examinations. Plain x-ray films of the neck and shoulder were important for stretches/avulsions with associated injuries, GSWs, and suspected TOSs. The diaphragm level was checked by a review of chest x-ray films. Patients suspected of having supraclavicular stretch/avulsion injuries underwent cervical myelography followed by computed tomography scanning. Magnetic resonance imaging of the brachial plexus and the cervical spine was performed for suspected cases of TOS and those of tumors. Angiography was performed in some cases of TOS and in a few tumor cases. During surgery, all lesions with some degree of physical continuity underwent direct electrical stimulation above and below the lesion, as well as NAP recordings.57 The results of histological studies of resected neural tissue were correlated with preoperative clinical findings and the results of intraoperative electrical studies. Postoperative follow-up review included outpatient visits during which the strengths of individual muscles and muscle groups were graded and EMG examinations were performed. Almost all patients (93%) returned for at least one postoperative visit. Further follow-up review was accomplished by subsequent visits (70%), telephone calls (20%), and/or contact via the mail (10%). In cases in which follow up beyond 18 months was not possible, the patient’s postoperative status was represented by findings from the last documented clinical visit.

Operative Techniques

The operative approach was usually anterior.12,30 Nevertheless, 17% of patients with tumors, 10% of those with GSWs involving the lower roots and trunk, and 60% of patients with TOS were treated using a posterior subscapular procedure with resection of the first rib.17 The surgical anatomy of and operative techniques for both approaches to the plexus have been reviewed previously.12,29,31

External neurolysis was performed by freeing segments of the plexus element(s) proximally and distally and alternatively working toward injured segments in a circumferential fashion around the element. This was usually performed using a No. 15 scalpel blade or Metzenbaum scissors.

Intraoperative Electrical Studies

Recording of NAPs for supraclavicular plexus lesions was performed intraoperatively by using a tripolar stimulating electrode, which was placed directly on an extradural
spinal nerve, and a bipolar recording electrode, which was placed on a segment of a more distal plexus element such as the trunk or its division(s).\textsuperscript{23} Stimulating and recording electrodes were separated by 3 to 6 cm.\textsuperscript{54} If a spinal nerve was regenerating adequately and 3 to 4 months had elapsed since injury, an NAP with a low amplitude and slow conduction was recorded (Fig. 1).\textsuperscript{27} If the nerve was not regenerating, the trace was flat (Fig. 2). If there was only a preganglionic injury to the dorsal root, the NAP was recordable, but exhibited a relatively large amplitude and rapid conduction compared with the findings of a regenerative potential.\textsuperscript{23,54} Such an NAP could be recorded because sensory fibers distal to the dorsal root ganglion had been spared, despite a more proximal disconnection from the spinal cord and complete clinical loss of function distal to the lesion. On the other hand, if there was severe postganglionic damage on the extradural root or spinal nerve, or if there was both pre- and postganglionic damage, no NAP was recorded. If a regenerative NAP was found, only neurolysis was performed. If there was no NAP, resection of the spinal nerve and the more distal and involved plexus element(s) was performed. Thus, when NAP traces were flat or preganglionic, we sectioned the spinal nerve (extradural root) back toward the dura mater.\textsuperscript{28} With the aid of magnification, we exposed the spinal nerve proximally by removing some of the bone structure around the element. If sectioning did not allow us to visualize the fascicular structure from which to lead out grafts, we did not attempt graft repair at that level. In cases in which the roots were avulsed or severely damaged at an intradural level, the proximal extradural root or spinal nerve was scarred on the cross-section and did not usually have a discernible fascicular structure. If a fascicular structure was found, however, grafts were led out from that level. In the event there was doubt about fascicular structure, a frozen section of the proximal stump of the spinal nerve was examined.\textsuperscript{36}

If the spinal nerve was stimulated close to its foraminal exit and recording electrodes were placed over the upper

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**Fig. 1.** Intraoperative photograph and trace demonstrating NAP recording in a patient with a stretch injury. Intraoperatively, the NAP was recordable when the upper trunk (arrow) was stimulated and a recording was made from the lateral cord (arrowhead). C = clavicle; SSN = suprascapular nerve; Trig = trigger.

**Fig. 2.** Intraoperative photograph and trace demonstrating NAP recording across a neuroma in continuity of the upper trunk. The stimulating electrode on C-5 (arrow) and the recording electrodes on the anterior division (arrowhead) are placed across the lesion to record the NAP. No NAP could be recorded across the lesion.
posterior cervical spine or the scalp corresponding to the contralateral motor area, a somatosensory response was recorded if the posterior or dorsal root at that level was intact. Such an SSEP or evoked cortical potential indicated an intact dorsal root, although the results of animal studies have indicated that as few as 100 intact fibers can produce such a response.

If the SSEP or evoked cortical potential of the dorsal root was positive, there was usually, but not always, continuity to the ventral (motor) root. Recent work has advocated percutaneous magnetic stimulation of the motor strip and recording from the spinal nerve as a test of the integrity of the ventral root; however, our experience and that of others with this procedure are too nascent for inclusion in this series. Because of our experience with both SSEP and NAP recordings, we currently use the latter almost exclusively, not only for lacerations and GSWs in continuity but also for supra- and infraclavicular stretch injuries.

Suture Repairs

Once an element was electrically determined to have no recordable conduction and a short nerve gap was found after resection, end-to-end epineurial repair was performed. The same procedure was conducted for transection in which end-to-end opposition could be gained with minimal tension. When the gap was too great for end-to-end repair, autografts, usually sural, were harvested and a grouped interfascicular repair was performed (Fig. 3). Grafts were frequently necessary for lengthy lesions in continuity that were not associated with recordable NAPs. Grafts were also necessary when stumps of transected nerves were retracted and could not be approximated without tension.

A split repair was performed when a portion of the element’s cross-section was more involved or damaged than the rest. If no NAP was recorded across the more damaged segment after it was split away, it was resected and repaired by grafts. Excess scar tissue was removed from the segment to be spared, with care taken not to sacrifice the fascicular structure.

Operative Techniques for Tumors

An anterior supraclavicular and/or infraclavicular approach was performed in 83% of the 141 patients harboring benign tumors who were surgically treated at LSUHSC. A smaller percentage of patients (17%) underwent a posterior subscapular approach.

The first step in the removal of nerve sheath tumors was to isolate and identify adjacent plexus elements and structures to prevent damage to them. The proximal and distal elements directly involved with the tumor were then isolated. Using microsurgical techniques, fascicles could be gently dissected from the tumor in the extracapsular plane. As the tumor was gradually exposed and the proximal and distal poles were approached, care was taken to isolate fascicles entering either the substance of the tumor or its capsule (Fig. 4). Intraoperative electrical stimulation and NAP recordings provided data that permitted sacrifice of non-functioning fascicles that entered and exited the tumors, which permitted removal of the tumor as a single mass.

Results

Several factors affected functional outcomes, including...
Outcomes of surgery for 55 stretch injuries to the C-5 and C-6 nerves with complete loss of function

<table>
<thead>
<tr>
<th>Operation</th>
<th>No. of Patients</th>
<th>Average Outcome</th>
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<tbody>
<tr>
<td>C-5 &amp; C-6 grafts</td>
<td>34</td>
<td>Grade 3 (19)</td>
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<tr>
<td></td>
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<td>Grade 3–4 (7)</td>
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<tr>
<td></td>
<td></td>
<td>Grade 4 (8)</td>
</tr>
<tr>
<td>C-5 nerve grafts, C-6 nerve avulsed, descending cervical plexus used</td>
<td>5</td>
<td>Grade 2–3</td>
</tr>
<tr>
<td>C-5 nerve avulsed, C-6 nerve grafts, descending cervical plexus used</td>
<td>2</td>
<td>Grade 3–4</td>
</tr>
<tr>
<td>C-5 &amp; C-6 neurolysis (NAPs present)</td>
<td>12</td>
<td>Grade 3–4</td>
</tr>
<tr>
<td>C-5 neurolysis, C-6 nerve grafts</td>
<td>2</td>
<td>Grade 3–4</td>
</tr>
</tbody>
</table>

Supraclavicular Stretch Lesions

Supraclavicular stretch patterns included spinal nerves C5–6 (15%), C5–7 (20%), and C5–T1 (57%), or other patterns such as nerves at C8–T1 or C7–T1 (8%).

Stretch Injuries to the C-5 and C-6 Nerves. Fifty-five stretch injuries involving the C-5 and C-6 nerves were treated. Weakness or paralysis and eventual atrophy occurred in the supraspinatus, infraspinatus, deltoid, biceps–brachioradialis, and supinator muscles. Patients selected for surgery had little or no evidence of a clinical or an EMG-verified return of function within 4 months and underwent surgical exploration.

Twelve patients underwent C-5 and C-6 neurolysis because NAPs could be recorded across lesions in continuity with good results. Most (43) of the patients with C-5 and C-6 lesions who were selected for surgery required graft repairs (Table 3). Of the 43 graft repairs, 34 involved direct grafts leading out from both the C-5 and C-6 roots to the anterior and posterior divisions of the upper trunk. As a result, 19 patients recovered to Grade 3, eight patients to Grade 4, and seven patients to Grades 3 to 4. Five patients had an isolated C-6 avulsion and underwent direct graft repairs to the C-5 nerve with a supplemental or nerve transfer from the descending cervical plexus. Outcomes in this group averaged only Grade 2 or 3. In recent years (1999–2002) this group of patients underwent medial pectoral branch transfers to the musculocutaneous nerve with improved results for the biceps muscle. Two patients had a C-5 avulsion and underwent graft repairs to the C-6 nerve with supplements from the descending cervical plexus, resulting in a better recovery grade of 3 or 4. More recently, several patients in this category have undergone a procedure in which an anastomosis is created between the accessory and suprascapular nerves, with improved results for the supraspinatus muscle.

In the C-5 and C-6 group, return of elbow flexion via the biceps–brachialis muscle was always better than shoulder abduction by the deltoid and supraspinatus muscles.

Eight patients with C-5 and C-6 patterns of loss of function and apparent clinical and EMG-verified preservation of the C-7 nerve had, on intraoperative dissection and NAP recordings, serious involvement of C-7. If the C-7 nerve was resected because of absent NAPs, postoperative loss did not increase and the C-7 nerve could still be used to supplement the other repairs.

Stretch Injuries to the C5–7 Nerves. Seventy-five patients with stretch injuries to the C-5, C-6, and C-7 nerves had the same pattern of loss previously described for C5–6 injuries, plus some weakness of the elbow, wrist, and finger extension. Loss of wrist and finger extension and weakness of the flexor profundus muscle varied because of a dominant input of the C-8 nerve to these muscles in some patients. This group was selected for surgical exploration and repair because they suffered complete or persistent severe clinical loss, at least in the C5–6 distribution (Table 4). Compared with the C5–6 stretch injury group, the C5–7 group had more roots avulsed. As a result, in 26 cases nerve repair was performed with grafts from only one or two proximal spinal nerves. In 10 patients with C-6 and C-7 avulsions, direct graft repairs were led from the C-5 nerve with a supplement from the descending cervical plexus. This maneuver resulted in recovery averaging only Grade 2 to 3. In 10 cases of isolated C-7 avulsions, direct graft repairs from C-5 and C-6 nerves to the anterior and posterior divisions of the upper and middle trunks resulted in an average recovery of Grade 3. Six patients who had C-5 avulsions and received direct graft repairs to C-6 and C-7 nerves achieved an average recovery grade of 3.5. In recent years (1999–2002), if usable outflow to the suprascapular nerve was poor, the accessory nerve was transferred to this nerve. If usable outflow to the biceps muscle was poor, an anastomosis was created between medial pectoral branches and part or all of the musculocutaneous nerve (Table 4).
During surgery 1040 spinal nerves were evaluated in 208 patients. Despite attempts to select favorable cases for repair, 470 elements had irreparable proximal damage, usually due to avulsion: 35% at the C7–8 level, 35% at the C7–T1 level, and only 10% at the C-5 level. Direct graft repairs were performed on the remaining 570 spinal nerves. Graft repair of two spinal nerves per patient was performed in 54 cases, and three or more spinal nerves per patient were repaired in 76 cases. Because regenerative NAPs were measured distal to their lesions, 35 of the patients required only neurolysis without graft repairs on one or more plexus elements. Nine patients underwent split graft repair of the C-5 or C-6 nerve and its outflows. Restoration of significant shoulder abduction and elbow flexion was obtained in approximately 40% of the cases and elbow extension was obtained in 30%, despite severe preoperative losses. Unfortunately, useful wrist or finger movement was seldom achieved. Most of the better functional grades were due to shoulder and upper-arm recovery rather than distal function.

208 patients (57%). The presenting and usually persistent symptom was total upper-extremity paralysis or flail arm. This group of patients had the lowest spontaneous recovery rate (4%).

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Only 35% of the patients with C5–T1 stretch injuries gained an overall functional outcome of Grade 3 or better (Table 5). As a result, in the last few years, most patients with C5–T1 stretch injuries or flail arms have undergone neurotization (nerve transfers) in addition to any direct graft repairs. These transfers have usually involved accessory nerve to suprascapular nerve or posterior division of upper trunk and intercostal nerves to musculocutaneous nerve. As a result, grades for shoulder and biceps muscles have increased by an average of 0.85.

**Infraclavicular Stretch Lesions**

Of the 143 infraclavicular brachial plexus stretch injuries, 35 cases involved 78 elements at the division or cord level (Table 6). Repair of lateral cord stretch injuries produced a mean grade of 3.8 for grafts, 4.3 for sutures, and 4.5 for neurolysis based on the presence of a positive NAP. Twenty-nine repairs of medical cord stretch injuries did not succeed as well. Graft repairs produced a mean grade of 1.2 and suture a mean grade of 2.2, whereas a mean grade of 3.9 was obtained for neurolysis based on the presence of a positive NAP. Despite difficult dissections due to prior vascular repairs, 25 posterior cord lesions did better than medial cord lesions. Graft repairs resulted in a mean grade of 3, suture a mean grade of 3.6, and neurolysis a mean grade of 4.1.

Surgical exploration from the clavicle to the upper arm was performed on 337 elements in 108 patients who had cord-to-nerve lesions. Care was needed to preserve the axillary artery and vein, especially in cases in which there had been previous dissection with or without vascular repair. Cumulative mean outcomes for the lateral cord to its outflows were Grade 3 for grafts, Grade 4 for sutures, and Grade 4.2 for neurolysis. In the patients with medial cord-to-ulnar nerve injuries (48 elements), 13 graft repairs resulted in poor outcomes, with a mean of grade of 1.4. A mean grade of 3.6, however, was achieved if NAPs could be recorded following neurolysis, even in those cases in which initially there was a complete loss of function. Sixty-five of the elements were posterior cord-to-radial nerve injuries. Of those, 32 graft repairs resulted in a mean grade of 2.7 and 29 neurolysis procedures resulted in a mean grade of 4.1. Of the 78 posterior cord-to-axillary nerve injuries, 38 had isolated axillary nerve involvement, 11 were associated with suprascapular nerve injuries, 13 were associated with the
Outcomes of brachial plexus lesions

**TABLE 7**

<table>
<thead>
<tr>
<th>Type of Lesion</th>
<th>Neurolysis (NAPs present)</th>
<th>Suture</th>
<th>Graft</th>
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</thead>
<tbody>
<tr>
<td>lesions w/ complete loss</td>
<td>46/42 (91%)</td>
<td>21/14 (67%)</td>
<td>135/73 (54%)</td>
</tr>
<tr>
<td>(202 elements)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lesions w/ incomplete loss</td>
<td>82/78 (95%)</td>
<td>6/5 (83%)</td>
<td>3/2 (67%)</td>
</tr>
<tr>
<td>(91 elements)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total (293 elements)</td>
<td>128/120 (94%)</td>
<td>27/19 (70%)</td>
<td>138/75 (54%)</td>
</tr>
</tbody>
</table>

* Results are given as total number of elements/number of elements recovering to Grade 3 or better.

**TABLE 8**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Elements</th>
<th>Neurolysis</th>
<th>Suture</th>
<th>Graft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in Continuity</td>
<td>Sharpe</td>
<td>Blunte</td>
<td>Totals</td>
</tr>
<tr>
<td>no. of plexus cases</td>
<td>20</td>
<td>28</td>
<td>23</td>
<td>71</td>
</tr>
<tr>
<td>no. of plexus elements</td>
<td>57</td>
<td>83</td>
<td>61</td>
<td>201</td>
</tr>
<tr>
<td>neurolysis (NAPs present)</td>
<td>26/24</td>
<td>0/0</td>
<td>0/0</td>
<td>26/24 (92%)</td>
</tr>
<tr>
<td>primary suture</td>
<td>0/0</td>
<td>31/25</td>
<td>0/0</td>
<td>31/25 (81%)</td>
</tr>
<tr>
<td>secondary suture</td>
<td>9/7</td>
<td>12/8</td>
<td>5/3</td>
<td>26/18 (69%)</td>
</tr>
<tr>
<td>secondary graft</td>
<td>22/17</td>
<td>40/21</td>
<td>56/25</td>
<td>118/83 (53%)</td>
</tr>
<tr>
<td>total elements</td>
<td>57/48</td>
<td>83/54</td>
<td>61/28</td>
<td>201/130 (65%)</td>
</tr>
</tbody>
</table>

* Results are given as total number of elements/number of elements recovering to Grade 3 or better. Primary denotes repair within 72 hours after injury; secondary denotes delayed repair after several weeks.

posterior cord, and 16 were associated with other lesions. Overall, the 48 graft repairs performed in this group produced a mean grade of 3.5, and 28 neurolysis procedures in which an intraoperative NAP was recorded had a mean recovery grade of 4.7.

**Gunshot Wounds**

One hundred eighteen nerve injuries were due to GSWs. Most of the 293 plexus elements that were surgically treated had some gross continuity when surgically exposed. Only 8% of elements with complete loss distal to the lesion were found to have total physical disruption during surgical exploration. Some lesions in continuity recovered spontaneously, but others displayed no signs of reversal or reinnervation after several months. In these cases, exploration and intraoperative NAP recording was performed. Of the 293 in-continuity elements that were explored and evaluated, 120 had recordable NAPs and, in response to neurolysis, function improved to Grade 3 or better in 94% of these cases (Table 7). Elements that did not have early evidence of regeneration usually required repair. Thus, 156 of the 202 suspected completely injured elements required resection and repair, as indicated by intraoperative electrical evaluation. Pathological examination of resected specimens confirmed neurotmesis or Grade IV injuries based on the Sunderland classification.

Repairs were relatively effective for predictable elements such as the upper trunk and the C5–6 nerve roots, and for lateral and posterior cords and their outflows. Acceptable results were achieved by grafts in 73 of 135 cases in which there was complete loss and by suture in 14 of 21 of these cases. Grafts worked as well as end-to-end sutures in the GSW series, perhaps because they were relatively short (1–2.5 in). Recovery occurred in severe C-8, T-1, lower trunk, and medial cord injuries when the nerve was in continuity and NAPs were recorded. Graft or suture repair of these elements did not result in useful recovery, except in a few pediatric cases.

Of the 91 elements preoperatively assessed as having incomplete loss, intraoperative stimulation and NAP studies showed that nine were not regenerating adequately. These discrepancies were usually due to a variation in anatomy at the infraclavicular level. These lesions required repair by suture or grafts.

**Plexus Lacerations**

Plexus lacerations were either sharp (caused by knives or glass) or blunt (caused by automobile metal, fan and motor blades, chain saws, or animal bites). Sharp transections accounted for injuries to 83 plexus elements and blunt transections to 61 (Table 8). One third of the patients with lacerating injuries to the plexus underwent acute surgical exploration because of suspected or angiographically proven vascular injuries. There were 57 plexus elements in 20 patients in whom the lesions were in some degree of continuity, despite the laceration. Twenty-six elements associated with a positive NAP across the lesion were treated with neurolysis; 24 of these elements recovered to Grade 3 or better. In cases in which the NAP recordings showed no transmission beyond the lesion in continuity, nine elements were treated with delayed suture. In seven of these cases the elements recovered. Graft repairs were performed on 22 other elements, 17 of which recovered. Grade 3 or better levels were achieved in 48 (84%) of the 57 involved elements.

When referrals were expedited and surgery occurred within 72 hours, outcomes were favorable for sharp transections; 25 (81%) of 31 recovered to Grade 3 or better. Due to delays in referral or transport, repair of 40 sharply transected elements was delayed. In this group in which graft rather than suture was necessary because of stump retraction, the overall recovery rate of this procedure was 53%. Repairs were delayed by choice in lesions from blunt transections because the extent of damage was initially difficult to assess accurately. Thus, 56 of 61 blunt transections required graft repair. Secondary suture was possible in only five cases. Overall recovery in this category was 46%.

**Thoracic Outlet Syndrome**

One hundred sixty operations were performed on 151 patients by using either an anterior (62 patients) or posterior (98 patients) subscapular approach (Table 9). Unilateral symptoms were present in 142 patients; nine others had bilateral symptoms requiring bilateral surgery. The patients ranged in age from 11 to 70 years; more than half were between 30 and 40 years of age and female patients were slightly more prevalent.

Seventy-eight patients had undergone a total of 127 operations before undergoing TOS surgery at LSUHSC. The most common procedure that was performed prior to referral was transaxillary first rib excision. This occurred in 52 patients once and in five patients twice. Eleven patients had undergone cervical rib removal and 27 had undergone ei-
ther carpal tunnel release or ulnar transposition. Pain and paresthesias were lessened in most cases (89%), but 17 patients experienced persistent residual pain. Motor deficits in patients with true neurogenic syndrome or Guillain–Sumner hands improved in some, but severe C8–T1 weakness related to prior surgery was less likely to reverse. By comparison, mild motor deficits improved in 22 (73%) of 30 cases. In either category, finger extension or flexor profundus function improved more than loss of function in the intrinsic muscles of the hand did, although a few patients experienced improved function of the intrinsic muscles by one or two grades.

Nerve Sheath Tumors

There were 161 cases in which nerve sheath tumors arose from the brachial plexus; 104 of these involved the supracleavicular and 57 the infraclavicular portion. There were 55 solitary neurofibromas, 54 schwannomas, 32 neurofibromas associated with VRD, and 20 malignant nerve sheath tumors. Results for the 141 patients with benign nerve sheath tumors presenting with or without pain and with or without weakness are summarized in Table 10.

Of the 54 patients who underwent surgery for schwannomas, 52 (96%) presented with a palpable mass and all but one experienced dysesthesia when the mass was percussed. The male/female ratio was equal. Six patients experienced a decline in motor function due to prior biopsy procedures or attempts at resection. These iatrogenic injuries were associated with divided fascicles, and required graft repairs as well as tumor removal.

Fifty-five patients ranging in age from 4 to 71 years (mean 38.3 years) associated with divided fascicles, and required graft repairs as well as tumor removal.

<table>
<thead>
<tr>
<th>Table 9: Outcomes of 150 surgeries in 151 patients with TOS</th>
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<tbody>
<tr>
<td>Outcome</td>
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<tr>
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</tr>
<tr>
<td>pain</td>
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<td>motor function</td>
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The mean age of these 20 patients at presentation was 45 years. Fourteen underwent local resections and six underwent local resections with margins. Subsequently, six patients who still had positive tumor margins underwent forequarter amputation of the shoulder and arm. Tumor removal brought some pain relief in most, but not all patients; however, motor symptoms were seldom helped. Of the 20 patients, 14 died by the time of this review. The average length of survival was 25 months (range 6–119 months) in the neurosarcoma group and 58 months (range 18–143 months) in the sarcoma group in which the origins were different from nerve.

Discussion

Stretch Injuries Including Avulsion

Stretch injuries are the most common and difficult brachial plexus injuries to manage. Most injuries are secondary to motor vehicle accidents, especially those involving motorcycles. The torsional force generated during the accident moves the head and neck in one direction and the shoulder and arm in another, resulting in severe stretching of soft tissues including nerves and, less frequently, vessels. Avulsion of one or more nerve roots is common.

Historically, a conservative nonsurgical approach has predominated. In Leffert's summary of early 20th century literature, many cases of stretch injury were birth palsies and only a few were adult traction injuries. Occasional success with surgery was reported, but as a whole, the limited amount of recovery gained was discouraging. When, whether, and how to manage these injuries surgically was and remains controversial.

Some surgeons support an aggressive approach with surgical correction of injured elements as early as possible or, more recently, even replantation of avulsed roots. We favor a period of conservative management of 3 to 4 months prior to operative exploration. Early evidence of spontaneous recovery takes longer to manifest in cases of severe nerve injury. The element(s) of origin was sometimes necessary to save the remainder of the plexus and to palliate pain. Of the 32 patients, tumors were completely removed in 18 (56%) and partially resected in another 14 (44%). Function was improved in most patients, but seven patients (22%) required graft repairs.

Malignant Nerve Sheath Tumors. Seventeen patients harbored tumors that were malignant schwannomas or neurogenic sarcomas, and three other patients had sarcomas of different origins: spindle cell, synovial, and fibrosarcoma. The mean age of these 20 patients at presentation was 45 years. Fourteen underwent local resections and six underwent local resections with margins. Subsequently, six patients who still had positive tumor margins underwent forequarter amputation of the shoulder and arm. Tumor removal brought some pain relief in most, but not all patients; however, motor symptoms were seldom helped. Of the 20 patients, 14 died by the time of this review. The average length of survival was 25 months (range 6–119 months) in the neurosarcoma group and 58 months (range 18–143 months) in the sarcoma group in which the origins were different from nerve.
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Stretch injuries than it does in cases of GSWs, because the lesions are longer in the former case.\textsuperscript{4,41} If there is no clinical or electrodiagnostic evidence of recovery within 3 to 4 months, the injury is assumed to be severe and the patient is deemed a candidate for surgery (Fig. 5). Discovery of extensive paraspinal denervation, rhomboid loss, diaphragm paralysis, winged scapula, Horner syndrome, intact sensory conduction(s), and abnormal findings on myelograms suggest avulsion(s) and the appropriate level(s), and help operative planning.\textsuperscript{9,16,37,51}

Stretch Injuries to C-5 and C-6 Nerves

In C-5 and C-6 nerve lesions, the distribution of loss was predictable. Thirty percent of patients spontaneously began to regain a significant amount of function, usually by 3 to 4 months after injury.\textsuperscript{41} Operatively, one seventh of the patients had serious C-7 nerve involvement, despite clinical and electrical evidence to the contrary. Stretch injuries to the C-5 and C-6 nerves had the most favorable outcomes following repair, regardless of whether the C-7 nerve was involved. Direct repair of one or both spinal nerves was common. Nerve transfers for C5–6 stretch injuries were required less frequently than in other injury patterns, but in recent cases it was used in conjunction with direct repair. Some patients who had isolated C-6 avulsions and underwent direct graft repair to the C-5 nerve were helped by a transfer of medial pectoral branches to the musculocutaneous nerve.\textsuperscript{6} Conversely, some patients with C-5 avulsions who underwent graft repairs to the C-6 nerve with a supplement from the descending cervical plexus were also helped by a transfer of the distal accessory nerve to the suprascapular nerve.\textsuperscript{10,52}

Stretch Injuries to C-5, C-6, and C-7 Nerves

In C5–7 nerve lesions, loss of function included the triceps as well as the shoulder muscles and the biceps–brachialis, brachioradialis, and supinator muscles. Not many C5–7 injuries (12%) improved spontaneously during the early months after injury. Consequently, surgery performed for direct repair of the plexus, with or without nerve transfers, was of primary importance, even though avulsions were more common than those seen with C5–6 stretches. With C8–T1 muscle function spared, opportunities to substitute the pectoral branches for the biceps muscle were usually but not always present. In recent years the accessory nerve has also been transferred to either the suprascapular nerve or to the posterior division of the upper trunk. Outcomes were best for biceps–brachialis function, followed by shoulder function. There was only partial recovery in triceps function. Fortunately, relaxation of the biceps muscle can provide extension of the elbow due to gravity.

Stretch Injuries to C5–T1 Nerves (Flail Arm)

In lesions involving C5–T1 nerves, the most frequent pattern of loss was a completely paralyzed arm, or “flail arm.”\textsuperscript{57} If loss in this distribution was complete or severe, spontaneous functional recovery was at the lowest rate (4%) of all stretch injuries. Almost half the spinal nerves explored were avulsed. The ones that were not could sometimes be repaired. It is difficult to correct this pattern by direct repair, although some additional useful function is possible by performing nerve transfer.\textsuperscript{3,4,19,42,44,46,51} Each transfer (for example, intercostal-to-musculocutaneous nerve, or accessory-to-suprascapular nerve) contributes to functional recovery in only one muscle group.\textsuperscript{10,44} Unfortunately, sometimes these neurotized muscles contract only weakly. For these reasons, we occasionally added the descending cervical plexus or, less frequently, the phrenic nerve or branches of the accessory nerve that lead to the sternocleidomastoid muscle, to the accessory and intercostal transfers. Importantly, we directly repaired plexus elements that provided useful proximal outflow to maximize outcomes gained more distally with nerve transfers. The emergence of vascularized and neurotized free muscle grafts may eventually offer some hope for the patient with an otherwise irreparable flail arm.\textsuperscript{13}

Infraclavicular Stretch Injuries

Infraclavicular stretch injuries occurred less frequently than supraclavicular injuries, but functional loss was equally severe and often did not reverse with time. This experience varied from earlier observations.\textsuperscript{12,47} Infraclavicular injuries were often associated with axillary artery injury, shoulder dislocation or fracture, and humeral fracture, which made surgical exploration technically difficult.\textsuperscript{31} Sur-
surgery was selected if loss of function persisted for 3 to 4 months in the distribution of one or more elements in which there was potential for recovery. Suture and graft repairs produced favorable outcomes for lateral and posterior cords and their outflows, including the musculocutaneous, median, and axillary nerves. Recovery of muscles innervated by posterior cord–radial nerve was better for the triceps, brachioradialis, and extensor carpi radialis muscles than it was for supinator, extensor carpi ulnaris, and finger extensor muscles. Repair of the medial cord to the median nerve produced useful results, but repair of the medial cord to the ulnar nerve usually did not.

**Gunshot Wounds**

Gunshot wounds to the plexus can transect elements, but most often produce lesions in continuity. Depending on the missile caliber, acceleration, and range, the force associated with the injury will vary. Consequently, low-velocity missile injuries may display a significant return of function within a few months.

Although older literature concerning GSWs to the brachial plexus emphasizes that many lesions recover spontaneously, many cases in which high-velocity missiles were involved have failed to do so in our experience. Patients selected for surgery had complete and persistent loss of function in the distribution of one or more elements or incomplete loss of function attended by pain that was not alleviated by more conservative management. It is essential that clinicians evaluate each plexus injury by the element(s) involved and not just according to the plexus as a whole, because incomplete loss or recovery in the distribution of an element does not guarantee recovery of others. Intraoperative stimulation and NAP recording studies are important to the identification of those elements needing resection. Although the majority of lesions in continuity with complete preoperative loss of function were treated by resection because of the absence of NAPs, a significant number were spared because recordings showed evidence of regeneration. More than 50% of lesions repaired by grafts, and approximately 70% repaired by suture had successful outcomes. Often an associated vascular injury will warrant emergency repair. In addition to transections of a major vessel, GSWs involving the brachial plexus can produce pseudoaneurysms or arteriovenous fistulas, which can compress the plexus and produce progressive loss of function and severe pain. Injured elements need to be dissected and gently moved away from the area of vascular repair. It may also be necessary to perform a second operation for NAP recordings and neural repair.

In this series, a low incidence of serious complications was observed, but the decision for surgical intervention must always be weighed with the knowledge that complications and poor outcomes are possible. It is also essential that surgery be supplemented by intensive physical therapy, lengthy follow up and monitoring, and consultation with other specialists for further reconstructive or rehabilitative measures.

**Lacerating Injuries**

Primary repair is advised for sharply transected plexus elements, whereas secondary repair is reserved for bluntly transected injuries or those suspected to be in continuity. Most authors agree that urgent repair is indicated for sharp lacerations of the plexus, especially if the loss of function is complete in the distribution of one or more elements. The advantages of such acute or primary repair for sharply transected plexus injuries are numerous.

Thoracic Outlet Syndrome

Although infrequent, true neurogenic TOS does occur, and by 1998 we had cared for 20 such patients. These patients had weakness of the intrinsic muscles of the hand and, in most cases, intrinsic muscle atrophy. Electromyography studies revealed reduced ulnar motor and sensory conduction and median motor conduction. Some, but not all, of these patients had a cervical rib or an elongated transverse process at C-7. Most patients underwent surgery performed via the anterior approach and intraoperative recordings were performed by stimulating spinal nerves and recording from their trunks.

An operation may be indicated in the typical patient with TOS for persistent pain, neurological symptoms, or, less frequently, worsening clinical or electrical findings despite rest. Because the diagnosis of TOS is one of exclusion, surgery can only be undertaken after ruling out other causes of shoulder or arm pain. Surgery can be helpful for some patients thought to have TOS, but it may not relieve all TOS-like symptoms and it is not without risk. Good outcomes occur for the majority of TOS operations in well-selected patients, but the results do not alleviate all pain or reverse severe weakness, especially that related to the C-8 and T-1 nerves.

Unique in this series of patients with TOS was their operative evaluation by NAP recordings. Abnormalities included not only diminished NAP conduction velocity, but also markedly reduced amplitudes, especially from T-1 and C-8 to the lower trunk in patients with a Gilliatt–Sumner hand. Recordings of NAPs obtained in patients with neural symptoms but no clinical or EMG findings of loss were abnormal in many cases, but not as dramatic as those obtained in patients with true neurogenic TOS. Both conductive and...
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structural abnormalities, if present, began close to the spine. These observations suggest the need for neurolysis close to the spine in both groups of patients.

A posterior subscapular approach is recommended to treat TOS if one of several conditions are present: 1) prior rib excision that has left a significant remnant attached to the spine; 2) a large cervical rib; 3) injury to lower elements of the brachial plexus; or 4) a case in which a previous anterior surgery was performed during which neurolysis was performed, but the patient is still symptomatic. Not all of these patients were helped by a posterior procedure. Although a winged scapula was found infrequently, it did occur in 5% of our patients. An anterior approach provided adequate access to the lower elements, particularly in patients with TOS who had not undergone surgery previously. Furthermore, an anterior approach provided a view of the effects of any constricting bands or anomalous anatomy on the plexus, which was not always available by posterior approach. Pleural opening or phrenic loss sometimes complicated an anterior approach.

Nerve Sheath Tumors

We reviewed the surgical approaches and results of operations in 161 tumors (141 benign and 20 malignant) involving the brachial plexus. Excluded were other benign and malignant lesions not of nerve sheath origin. These have been relatively recently summarized in a published series from LSUHSC.21 Management of nerve sheath tumors has been a matter of debate for decades.11 Due to recent clinical experience, however, this management has changed, indicating that many benign nerve sheath tumors can be safely resected regardless of their histological characteristics.14,22

Most solitary neurofibromas and benign schwannomas could be removed with the aid of loupe magnification and NAP recordings. With schwannomas, there is usually a single fascicle entering and exiting the lesion, whereas in neurofibromas there are several fascicles or one large contributing fascicle and an exiting fascicle that does not transmit. The tumor itself is usually removed as a solitary mass, unless it is quite large, in which case a piecemeal resection and use of the Cavitron ultrasonic aspirator may be necessary.

Surgery usually preserved function and lessened pain, but outcomes were better when the tumors were small or had not been surgically treated previously. Postoperative pain or functional deficits occurred more commonly in patients who had previously undergone an attempted removal or biopsy sampling. Removal of neurofibromas associated with VRD could be difficult, but that was not always the case. Some tumors associated with VRD can, of course, occur at multiple loci or be plexiform or longitudinal in nature, making total removal difficult.

Malignant tumors tended to increase rapidly in size over a period of weeks or months, and appeared relatively large on initial presentation. Such tumors often are firmer and more attached to adjacent soft tissues, such as vessels, muscles, and bones, than benign counterparts such as schwannomas or neurofibromas.11,14 Consequently, malignant tumors rising from the plexus pose complex technical challenges22,24 and treatment must be individualized.50,52 En bloc resection or interscalpulothoracic amputation is recommended for some patients with infraclavicular neurosarcoma of the brachial plexus, but may not be possible because of major vascular loss or proximal tumor extension. It is important to rule out metastasis to the lung, bone, and/or liver by appropriate imaging studies before proceeding with amputation or aggressive local resection.22,23 Amputation is seldom an option with supraclavicular plexus neurosarcomas, in which as thorough a resection as possible has instead been performed. Radiation therapy, chemotherapy, or both may follow resection, although these treatment modalities produce variable and unpredictable effects on these malignant lesions.

Conclusions

Brachial plexus injuries, entrapments, and tumors can cause significant disability, often in young people. Surgical repair of brachial plexus lesions can be complicated and requires not only operative skill and perseverance, but a thorough grasp of plexus anatomy and physiology. In this retrospective study we examined the outcomes of 1019 surgically treated brachial plexus injuries, entrapments, and tumors during a 30-year period. Functional outcomes following surgical repair were encouraging, depending on the timing of surgery, the plexus elements involved, and the type of injury or disease. Delays of more than 6 months after injury diminished the chance of functional recovery. The type of repair depended on the kind of lesion and the presence or absence of positive NAP recordings. Injuries that result in a lesion in continuity and positive NAP recordings have the most favorable outcomes. Generally, the results of repair by suture or grafts were best for injuries to the nerves of C-5, C-6, and C-7; those with upper and middle trunk involvement; those of the lateral and posterior cord and their outflows; and, occasionally, those involving the medial cord to the median nerve. This analysis indicates that exploration of brachial plexus lesions including tumors and some TOS cases is feasible and that favorable outcomes can be achieved if patients are carefully selected. Complications can occur, however, and outcomes are far from optimal. Further experimental and clinical work is needed.

References

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