Mechanisms of injury in operative brachial plexus lesions

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Object. The authors focus on injury mechanisms involved in 1019 operative brachial plexus injuries (BPIs) managed between 1968 and 1998 at Louisiana State University Health Sciences Center (LSUHSC).

Methods. Data regarding these mechanisms of injury were obtained via retrospective chart reviews of patients who had undergone operations at LSUHSC.

Five main mechanisms of injury to the brachial plexus occurred in the series. These included 509 stretch/contusion injuries (49%) with four patterns of presentation in 366 patients: 208 C5–T1 nerve injuries; 75 C5–7, 55 C5–6 injuries; and 28 involving the C8–T1 or C7–T1 nerves. Stretch/contusion injury was followed in frequency by gunshot wound (GSW), resulting in 118 injuries (12%). Most of the 293 involved plexus elements had some gross continuity when surgically exposed. Seventy-one lacerations involved the brachial plexus (7%), including 83 sharp lacerations caused by knives or glass; 61 blunt transections due to automobile metal, fan, and motor blades, chain saws, or animal bites.

Nontraumatic BPIs included 160 cases of thoracic outlet syndrome or 16% of the total of 1019 BPIs. There were 161 tumors (16%) of neural sheath origin including 55 solitary neurofibromas (34%), 32 neurofibromas associated with von Recklinghausen disease (20%), 54 schwannomas (34%), and 20 malignant nerve sheath tumors (20%) removed. Obstetrical BPI was not included in the original series; however, the current literature is reviewed in this paper.

Conclusions. The conclusion of this study is that the brachial plexus can be injured by multiple mechanisms of which stretch/contusion injury is the most frequently encountered, followed by GSWs.

Key Words • brachial plexus • stretch injury • thoracic outlet syndrome • nerve sheath tumor • neurolysis • anastomosis

CLINICAL MATERIAL AND METHODS

Between 1968 and 1998, 1019 patients with brachial plexus lesions were managed and underwent operative intervention at LSUHSC. Patient charts were reviewed retrospectively to determine the sex and age of each patient and mechanisms of injury resulting in the individual brachial plexus lesions. Obstetrical BPIs were not included in this LSUHSC series nor were patients with nonneural tumors and tumors of intraspinal origin. The minimum follow-up period for these cases was 18 months with a mean follow-up period of 42 months.

Radiological and Histological Evaluation

Plain x-ray films of the neck and shoulder were and are important for delineating injuries commonly associated with stretch/avulsion, as well as GSW detritus and associated bone abnormalities in suspected TOS. Chest x-ray films were evaluated for the presence of an elevation of a hemidiaphragm that might indicate ipsilateral phrenic nerve injury indicative of a proximal C-5 injury. Patients
with supraclavicular stretch/avulsion injuries underwent cervical myelography followed by CT scanning to assess the status of the egress of spinal nerves from the spinal cord. Magnetic resonance imaging of the brachial plexus and the cervical spine and, less frequently CT scanning and angiography, were performed in cases of suspected TOS and tumors.

The results of histological studies of resected tumors involving the brachial plexus were reviewed to confirm tumor types.

**Operative Approach**

An anterior operative approach was used in the majority of cases; however, a posterior subscapular approach with resection of the first rib was performed in 60% of patients with TOS, 17% of patients with tumors, and 10% of those with GSWs involving proximal spinal nerves, especially the lower ones. The operative techniques for both the anterior and posterior approaches have been previously reviewed.2,8,10

**Surgical Technique**

**Intraoperative NAP Recording.** Intraoperative NAP recording was used to determine the status of the injured plexus element. Low-amplitude, slow-conducting NAPs at 3 to 4 months postinjury were indicative of a regenerating spinal nerve, whereas NAPs were flat across the lesion in a nonregenerating nerve. A large amplitude NAP with rapid conduction occurred if there was a preganglionic injury to the dorsal root. Under these circumstances, the actual NAP was due to sensory fiber sparing distal to the dorsal root ganglion, despite a more proximal disconnection from the spinal cord and complete clinical loss of function distal to the lesion. With severe postganglionic damage to the extradural root, or to the spinal nerve, or with both pre- and postganglionic damage, a NAP could not be recorded. Intraoperative electrical stimulation and NAP recordings provided data that permitted sacrifice of nonfunctioning fascicles that entered and left the tumors, which permitted removal of the tumor as a single mass.3

**Neurolysis.** Neurolysis was performed if an intraoperative NAP indicated a regenerative NAP. External neurolysis was performed using a No. 15 scalpel blade or Metzenbaum scissors. Nerve segments were freed from surrounding tissue circumferentially both proximally and distally from either side of the injured segment toward and through the involved segment.

**End-to-End Suture Anastomosis Repair.** When NAP recordings were flat the spinal nerve or extradural root was sectioned back toward the dura mater for supraclavicular lesions. The spinal nerve was exposed proximally with resection of the first rib was performed in 60% of patients with TOS, 17% of patients with tumors, and 10% of those with GSWs involving proximal spinal nerves, especially the lower ones. The operative techniques for both the anterior and posterior approaches have been previously reviewed.2,8,10

**Graft Repair.** If a fascicular structure was found, but there was a large interneural gap, an end-to-end repair was not possible. Sural autografts were then led out from that level to enable a grouped interfascicular repair. Grafts were also used for lengthy lesions in continuity without recordable NAPs and for retracted stumps of transected nerves, which could not be approximated without tension. A split-repair was performed when a NAP could be transmitted across the lesion but a portion of the element’s cross-section had more damage than the remainder of the element. The damaged segment was then split away from the more normal-appearing nerve segment and if no NAP was recorded across this damaged segment after it was split away, it was resected and repaired by grafting. Excess scar tissue was removed from the segment to be spared, with care taken not to sacrifice the fascicular structure. Graft repair was not performed in the following cases: 1) if the fascicular structure from which to lead out grafts was not visualized; 2) in severely damaged or avulsed roots at an intradural level; or 3) if the proximal extradural root or spinal nerve was scarred on cross-section and did not have a discernible fascicular structure. Under these circumstances, nerve transfers were usually performed. Included were accessory to suprascapular nerve, descending cervical plexus to trunk divisions, and medial pectoral or intercostal transfers to musculocutaneous nerve.

**RESULTS**

Patients with 1019 BPIs reported on in the paper by Kim, et al.,9 ranged in age from 4 to 73 years, with a median age of 34 years. Of 1019 BPIs, 509 were due to stretch/contusion injury, which was the most frequent lesion resulting in 49% of the 1019 lesions (Fig. 1). Gunshot wounds resulted in 118 injuries (12%), and there were 71 brachial plexus lacerations (7%). Nontraumatic injuries involving the brachial plexus included 161 tumors of neural sheath origin, which comprised 16% of all plexus lesions, and TOS was associated with 160 injuries or 16% of brachial plexus lesions. Thirty cases of iatrogenic lesions were included in either the stretch/contusion or laceration groups. Birth palsy, or obstetrical injury, is another category of injury, but it was not included in the last LSUHSC brachial plexus study.

**Stretch/Contusion and Avulsion Injuries**

The 509 stretch/contusion injuries were divided into 366 supraclavicular and 143 infraclavicular categories.

**Supraclavicular Stretch/Contusion Injury.** Three hundred sixty-six supraclavicular stretch/contusion injuries were aggregated into four patterns in order of prevalence: 1) 208 C5–T1 nerve injuries (57%) presenting with a flail arm, (total upper-extremity paralysis [Fig. 2]); 2) 75 C5–7 nerve injuries (20%) resulting in weakness of C5–6 muscles, which include supra- and infraspinatus, deltoid, biceps/brachioradialis, and supinator muscles and in addition weakness of the C-7 muscles, which are the elbow, wrist, and sometimes finger extensors. Loss of wrist and finger extension and weakness of the flexor digitorum profundus muscles varied due to dominance of the unin-
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jured C-8 nerve input to these muscles in some patients. It was noted also that the C5–7 group had more avulsed roots than the C5–6 group. Another pattern of supraclavicular stretch/contusion injuries included 3) C5–6 nerve injuries, of which there were 55 lesions (15%) with weakness of the C5–6 muscle groups as defined previously (Fig. 3); or 4) 28 “other” injury patterns involving the C8–T1 or C7–T1 nerves (8%) (Table 1).

Infraclavicular Stretch/Contusion Injury. There were 143 infracervical brachial plexus stretch injuries. These injuries were further subdivided into the following: 1) division or cord levels; and/or 2) cord–nerve levels. Thus, 35 of the 143 total number of infracervical BPIs had 78 injured elements at a division or cord level. There were 337 injured plexus elements at a cord–nerve level in the remaining 108 infracervical BPIs, 78 of the 337 total...
caused by knives or glass or blunt and 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 injured 61 plexus elements (Table 4). One third of patients with lacerating injuries to the brachial 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 injury as a mechanism.

**Thoracic Outlet Syndrome**

One hundred sixty operations were performed in 151 patients. Either a posterior or anterior subscapular approach was used in 98 and 62 patients with TOS, respectively. Unilateral symptoms were present in 142 patients, whereas nine others had bilateral symptoms requiring bilateral surgery. Female patients were slightly more prevalent. The patients ranged in age from 11 to 70 years and more than half were between 30 and 40 years of age.

Seventy-eight patients had undergone a total of 127 operations before undergoing TOS surgery at LSUHSC. The most common procedure that was performed in 52 patients once and in five patients twice prior to referral was transaxillary first rib excision. Eleven patients had undergone cervical rib removal and 27 had undergone either carpal tunnel release or ulnar transposition.

**Neural Sheath Tumor**

There were 161 patients with neural sheath tumors arising from the brachial plexus: 104 involved the supraclavicular and 57 the infraclavicular portion of the plexus. Fifty-five patients (34%) underwent removal of solitary neurofibromas and 32 (20%) underwent removal of neurofibromas associated with von Recklinghausen disease. Fifty-four patients (34%) underwent schwannoma removal. There were 20 patients (12%) in whom resection of malignant neural sheath tumors was performed, which included 17 malignant schwannomas or neurogenic sarcomas, and three sarcomas of different origins, which were spindle cell, synovial, and fibrosarcoma.

**Obstetrical BPI**

Erb palsy is the most common type of birth palsy and is due to a C5–6 innervated upper trunk injury. As a result of this injury, the shoulder is adducted and internally rotated, the elbow is extended or slightly flexed, the forearm is pronated and the wrist flexed, all of which produce the so-called “waiter’s tip” posture. The muscles involved include the deltoid, responsible for abduction and elevation of the arm from 30° up to 90°, the supraspinatus, which initiates and continues abduction of the arm to 30°, the biceps and brachioradialis or elbow flexors, the supinator, which supinates the hand and the medial shoulder rotators, which include the pectoralis major, which also adducts the extended arm, the latissimus dorsi, and infraspinatus muscle.

Klumpke palsy results in atrophic paralysis of the forearm, small muscles of the hand and flexors of the fingers and thumb, and there is reduced sensation along the ulnar side of the arm, forearm and hand. Paralysis of the cervical sympathetic system can also occur. Klumpke paralysis is due, as well, to a birth injury in which the arm is forcibly abducted over the head. The timing of surgery is controversial. Al-Qattan recommends operating when the patient is 4 months of age if the indication for Erb palsy brachial plexus surgery is that of absence of elbow flexion against gravity.

**DISCUSSION**

There are few large series of BPIs and their mechanisms that have been reported in the recent literature. Peach, et al., reported on 218 patients with such injuries treated from 1996 to 2001 and the prevalence for each mechanism included 111 traction injuries (51%), 38 stab wounds (17%), and 42 GSWs (19%). These figures correlate well with the mechanisms presented in the LSUHSC BPI series, with the exception of the slightly higher frequency of GSWs in a study by Peach, et al. In their review, there were 16 birth injuries (7%) and 11 other

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**TABLE 2**

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<thead>
<tr>
<th>Injury Level</th>
<th>No. of Elements Injured</th>
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<tr>
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**TABLE 3**

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<th>Graft</th>
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<td>21</td>
<td>135</td>
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**TABLE 4**

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<th>Variable</th>
<th>Elements in Continuity</th>
<th>Sharp Transsection</th>
<th>Blunt Transsection</th>
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<td>28</td>
<td>23</td>
<td>71</td>
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<td>26</td>
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<tr>
<td>total elements</td>
<td>57</td>
<td>83</td>
<td>61</td>
<td>201</td>
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injuries” (5%). In a review by Terzis, et al.,21 the authors presented 204 operative posttraumatic BPIs and documented 119 patients with BPIs due to “high-velocity motor-vehicle accidents,” which were further subdivided into 73 motorcycle accidents and 46 auto accidents. Ten pedestrians sustained injury after being hit by a car. In the Terzis series GSWs caused 20 brachial plexus palsies (10%), and 55 patients were injured by an accident at work or other type of injury. One hundred twelve patients had avulsion of one or more roots, 48 had a supraclavicular postganglionic injury, and 43 had their trauma localized to the infraclavicular region. The difficulty of comparing the mechanisms found in the Terzis series with those found in the LSUHSC series highlights the lack of a consistent classification of mechanisms in the literature. “High-velocity motor-vehicle accidents” likely caused stretch/contusion injuries, although they may have resulted in blunt laceration injuries as well, both of which were individually delineated in the LSUHSC series. The GSW incidence of 10%, however, is in accordance with the LSUHSC series findings.

A brief synopsis of each mechanism category follows along with a review of the current literature for each.

**Stretch/Contusion Injury Including Avulsion.** The epidemiology of the stretch/contusion injury including avulsion injuries includes motor vehicle accidents, which caused the majority of these lesions and motorcycles were involved approximately twice as often as automobiles.15,20 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. Arm traction in a caudal direction affects the upper roots and trunks, and cephalad traction involves the lower plexus.

Avulsion of one or more nerve roots, which changes the lesion from a post- to a preganglionic injury, is common, occurring in approximately 70% of severe brachial plexus stretch avulsion injuries, but only in approximately 50% of plexus elements involved by stretch/contusion according to two published series.22,24 Avulsion results in the immediate irreversible loss of function and if it occurs close to the spinal cord might cause bleeding in the intradural cavity, and spinal cord injury. Avulsion may also be associated with the presence of pseudomeningoceles or arachnoid diverticula on myelography (Fig. 4A) or post-myelography CT scans (Fig. 4B), or MR imaging may indicate nerve sleeve disruption at the site of the nerve root injury. It is thought that nerve root pseudomeningoceles, although indicative of injury and often irreversible root injury, do not of themselves contribute to neurological dysfunction. Rarely, meningoceles may enlarge, extend intraspinally (Fig. 5A), and produce symptoms on their own of nerve root or spinal cord dysfunction.7 Magnetic resonance imaging signal intensity changes in the deep posterior cervical paraspinal muscles are related to denervation and indicate the presence of nerve root avulsion.22 Magnetic resonance imaging may show signal changes in the plexus from traumatic injury and, in addition, changes due to pseudomeningoceles (Fig. 5B).

**Gunshot Wound.** Gunshot wounds most often produce lesions in continuity, but can also transect elements. The force associated with the injury varies and depends on the missile caliber, velocity, and angle of incidence. Missile injuries to the brachial plexus can be produced by low-velocity shell fragments that damage nerve elements by direct impact or high-velocity gunshot injuries, which have three mechanisms of nerve damage: direct impact, resulting in nerve transection that has a lower incidence than shock wave and cavitation effects, which compress and stretch the nerve.14,18 Low-velocity missile injuries tend to be associated with less damage to the brachial plexus and surrounding structures, whereas high-velocity injuries of course result in more extensive damage and fail to recover spontaneously.

Each plexus injury caused by a GSW must be evaluated by the element involved and not by the plexus as a whole, which entails using intraoperative stimulation and NAP recording to identify elements needing resection. Associated vascular injuries warrant emergency repair, because GSWs can transect major vessels and can produce pseudoaneurysms or arteriovenous fistulas, both of which can compress the plexus and produce progressive loss of function and severe pain. In a review of 54 patients with GSWs involving the brachial plexus by Samardzic, et al.,19 16 patients (30%) had associated vascular injuries that required emergency repair.

**Lacerating Injury.** Primary repair is advised for sharply transected plexus elements, especially if the loss of function is complete in the distribution of one or more elements. Secondary repair, however, is reserved for bluntly transected injuries or those suspected to be in continuity.11 Early intervention is also indicated for increasing neurological deficit, which can be associated with a progressive pain syndrome due to a hematoma, arteriovenous fistula, or pseudoaneurysm.

**Thoracic Outlet Syndrome.** Thoracic outlet syndrome is a complex of signs and symptoms resulting from compression of the nerves and vessels supplying the upper limb by soft-tissue or bone anomalies at the thoracic outlet. Trauma in the area of the thoracic outlet may also predispose to TOS, which can present with pain, paresthesias, and often weakness of the affected upper extremity. Transaxillary first-rib resection as well as resection of the anterior scalene muscle and the medial aspect of the middle scalene muscle and brachial plexus neurolysis via a supraclavicular approach are often used.6,13

**Neural Sheath Tumor.** Tumors in the brachial plexus region comprise less than 5% of all tumors of the upper extremity. Thus, these tumors are uncommon lesions involving the brachial plexus.

Schwannomas have fascicles, which were displaced and “thinned-out” around the tumor and were bluntly dissected off the tumor capsule. An interfascicular dissection was performed at the proximal and distal tumor poles where single or sometimes two small fascicle(s) were seen entering and exiting the lesion. The nonfunctional proximal or distal fascicles were sectioned and the tumor was usually removed as a single mass.

Neurofibromas were removed in a similar fashion to the schwannomas by dissecting away adjacent and sometimes adherent nerves or elements and then separating fascicles from the tumor. Neurofibromas had more than one fasci-
cle both on tumor entry and exit and these were usually larger than those in the schwannomas. It was important to dissect out the fascicles at the proximal and distal poles of the tumor and to dissect them in a direction toward the mass. Fascicles entering and leaving the tumor were tested by stimulation of the proximal fascicles and recording NAPs from distal ones. As with the schwannoma, if traces were flat, the entering and exiting fascicles could be sacrificed and the tumor could be removed as a solitary mass. If NAPs were positive across entering and exiting fascicles, these fascicles needed to be traced into and out of the tumor and spared. Such fascicles sometimes had to be sacrificed to gain tumor resection and then fascicular defects were replaced by grafts.

Fig. 4. A: A myelogram revealing two right C6–7 pseudomeningoceles represented by extravasation of contrast dye as shown. B: An axial postmyelogram CT scan revealing a pseudomeningocele extending into the intervertebral foramen in the cervical spine.

Fig. 5. A: An axial T2-weighted MR image of a pseudomeningocele collection seen to the left of the thecal sac, which is being compressed to the right in the lower cervical spine. This intraspinal pseudomeningocele began at the site of the nerve root injury, indicates nerve root sleeve disruption, and has extended intraspinally. Pseudomeningoceles may or may not be associated with nerve root avulsions. B: A coronal T2-weighted MR image revealing bright signal changes of the brachial plexus. The patient had a traumatic injury to the plexus.
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Malignant tumors tended to increase rapidly in size over a period of weeks or months and to appear relatively large on initial presentation. Such tumors were firm and more attached to adjacent soft tissues, such as vessels, muscles, and bones than benign counterparts such as schwannomas and neurofibromas. Treatment must be individualized. En bloc resection or interscalpulolothoracic amputation was recommended for some patients with infraclavicular neurosarcomas of the brachial plexus. Amputation is seldom an option with supraclavicular plexus neurosarcomas in which as thorough a resection as possible was performed. Radiation therapy, chemotherapy, or both may have followed resection, although such treatment modalities produced variable and unpredictable effects on these malignant lesions.

Obstetrical Palsy. The incidence of obstetrical BPI has been recently documented by Ladfors, et al.,12 in a study in which 1,213,987 births were analyzed. A birth BPI was found in 2399 neonates (0.18%). Variables associated with BPI in newborns were shown in this study to include fetal macrosomia, shoulder dystocia, breech delivery, operative vaginal delivery, maternal diabetes mellitus, secondary arrest of dilation, and epidural anesthesia. Other risk factors shown in the literature include maternal obesity or excessive weight gain and the use of forceps during delivery.19 An increased birth weight, especially more than 4 kg, has been implicated by Giddins, et al.5 A persistent occiput posterior position has also been associated with an increased incidence of Erb palsy. Gherman, et al.,3 however, reviewed the obstetrical literature and suggested that brachial plexus palsies in infants may precede the delivery itself and occur in utero. This was supported by Ouzounian, et al.,16 in which a review of several of their cases of permanent Erb palsies showed no identifiable risk factors for injury.

Klumpke palsy involving the lower roots of the brachial plexus rarely occurs as a birth injury in modern-day obstetrics. There has been a sharp decline in vaginal breech births in which there is a risk of the requisite hyperabduction of the fetal arms. Regarding the use of the presence of biceps muscle function to predict the need for operative intervention, in a study by Al-Quattan1 all infants who recovered elbow flexion at 2 months of age were found to eventually recover completely normal limb function. Those who recovered elbow flexion by 3 months of age recovered almost normal function without need for any secondary surgery. If recovery of the biceps muscle had not begun by 3 months of age, the functional prognosis was considered poor, and surgical repair of the plexus was warranted. A study of 76 birth palsies at LSUHSC occurring from 1975 to 1992 showed that many infants did not recover biceps function until 4 to 9 months and yet did well. Thus, at LSUHSC, a more selective approach to operative intervention is chosen such that the decision for or against operation is made when the child reaches the age of 7 to 10 months. The neonate plexus unlike the adult plexus appears to respond to repair and to regenerate, despite a delay between injury and operation.

The determinant used to establish the need for surgery is usually complete loss of function persisting for this period of 7 to 10 months in the distribution of one or more plexus elements that can be helped by operation. Thus, findings in C-5, C-6, and C-7 and the upper and middle trunks are important. The majority of our patients have been managed without surgery.18 At the present time we have evaluated 185 children with birth palsies at LSUHSC, but have performed surgery in only 21.

CONCLUSIONS

Brachial plexus injuries are uncommon. When these injuries do occur the majority are due to stretch/contusions (50%) with almost half of the supraclavicular elements involved having avulsions. The next most common traumatic lesions were penetrating and were due to GSWs (12%) and lacerations (7%). Nontraumatic lesions causing damage to the brachial plexus were tumors (16%) and TOSs (16%). Other lesions of the brachial plexus include obstetrical palsies or birth injuries. In this paper we have highlighted these mechanisms of BPI and reviewed the current literature regarding these injuries to better enable the identification of causes of brachial plexus palsy when they do present.

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