Review Article

Brachial Plexus Injury : Mechanisms, Surgical Treatment and Outcomes

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This paper reviews the mechanisms of brachial plexus injury which includes the traumatic : stretch/contusions with or without avulsion, gunshot wounds(GSWs) and lacerations and the nontraumatic from tumors and the various etiologies of thoracic outlet syndrome(TOS). Another type of brachial plexus injury is that of obstetrical birth injury. The paper also reviews the anatomy of the brachial plexus and operative approaches with the anterior approach used in the majority of cases. The posterior subscapular approach with resection of the first rib is occasionally used for tumor resection, GSWs of the lower roots and trunk and the majority of patients with TOS. Surgical techniques and their indications in brachial plexus surgery are presented including nerve action potential(NAP) recording, neurolysis, end-to-end suture anastomosis repair and graft repair including split-repair. The mechanisms of brachial plexus injury are individually reviewed and results for each type of repair of same from the Louisiana State University Health Sciences Center(LSUHSC) experience with 1,019 patients between 1968-1998 are summarized. There were 509 (49%) stretch/contusion injuries, which was the majority lesion followed in number by brachial plexus GSWs (12%) and lacerations (7%). Nontraumatic brachial plexus injuries included tumors (16%) and TOS (16%). Obstetrical brachial plexus injury though not included with the 1,019 patients presented in a paper by Kim and Kline et al (J Neurosurg 98 : 1005-1016, 2003) are presented and the LSUHSC experience with these are included as well.

KEY WORDS : Brachial plexus · Injury · Surgical treatment · Outcome.

Introduction

Brachial plexus injury can result from traumatic mechanisms, which include stretch/contusions with or without avulsion, gunshot wounds(GSW) and lacerations. Nontraumatic injury can occur from tumors and various etiologies of the thoracic outlet syndrome(TOS). Another type of brachial palsy injury is that of obstetrical birth injury. The purpose of this paper is to review these mechanisms of plexus injury with regard to their surgical treatment and outcomes.

Anatomy of the Brachial Plexus

The C5-T1 spinal nerve roots form the brachial plexus; the C5-C6 and C8-T1 nerve roots join to form the upper and lower trunks, respectively, while the C7 nerve root continues as the middle trunk (Fig. 1, 2).

The three trunks next divide into anterior and posterior divisions at a clavicular level. At the level of the cords, which is distal to the clavicle, the plexus is termed the infraclavicular brachial plexus. The cords are formed as follows : the anterior divisions of the upper and middle trunks form the lateral cord and the lower trunk's anterior division continues as the medial cord; the posterior divisions from the upper, middle and lower trunks form the posterior cord. After giving off the axillary nerve, the posterior cord continues as the radial nerve. The medial cord gives a branch to the medial head of the median nerve and continues as the ulnar nerve, while the lateral cord gives a branch to the lateral head of the median nerve and continues as the musculocutaneous nerve.

To determine the portion of the brachial plexus that is injured, the following are important brachial plexus nerves and their associated muscles which are tested for evidence of nerve injury.

The long thoracic nerve from the C5, C6 and C7 nerve roots innervates the serratus anterior muscle. The dorsal scapular nerve, a branch of the C5 and C6 roots, supplies the levator scapulae and rhomboid muscles and a third branch, the nerve to the subclavius from the C5 and C6 nerve roots innervates the subclavius muscle, which is not clinically evaluable. Non-function of muscles innervated by these nerves suggests a proximal root injury and/or avulsion of the plexus from the spinal cord. The suprascapular nerve arises from the upper trunk above the clavicle and innervates the

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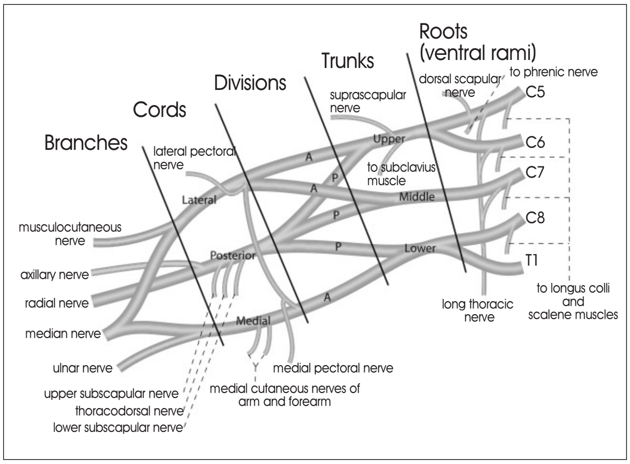

Fig. 1. Schematic diagram of the brachial plexus.

supra- and infraspinatus muscles.

A further distal branch of the lateral cord, the lateral pectoral nerve, innervates the clavicular head of the pectoralis major and weakness indicates lateral cord injury. The medial pectoral nerve arises from the medial cord and with the branches from the lateral pectoral nerve innervates the sternocostal head of the pectoralis major muscle. Examination of the pectoral major muscle is necessary to localize a cord level injury : pectoralis major clavicular head involvement implies lateral pectoral nerve injury and sternocostal head involvement, injury to both the lateral and medial pectoralis nerves, i.e. both medial and lateral cords.

The musculocutaneous nerve is a continuation of the lateral cord. It supplies the coracobrachialis and the biceps and brachialis muscles and continues distally as the lateral antebrachial cutaneous nerve.

The posterior cord after giving off the axillary nerve also gives off collateral branches to the muscles of the posterior wall of the axilla. The thoracodorsal nerve innervates the latissimus dorsi and the subscapular nerves innervate the subscapular and teres major muscles[15)].

Grading Neural Function after Brachial Plexus Injury

Each plexus element involved by injury should be graded individually as to pre- and postoperative neural function. The preoperative grades can then be combined and averaged, and the same is done for the postoperative function : a successful outcome is considered to be a grade 3 or higher; good recoveries are a grade 4 and excellent recoveries, a grade 5 [9,12)].

Radiological Evaluations

Plain x-rays of the neck and shoulder are important for the evaluation of brachial plexus injuries. They can document : 1) injuries commonly associated with stretch/avulsion, such as fractures; 2) shrapnel from GSWs and can also show 3) associated bony abnormalities in suspected thoracic outlet syndromes which can result in brachial plexus injury.

Chest x-rays can depict a hemidiaphragm indicating ipsilateral phrenic nerve injury, suggestive of a proximal C5 injury. Cervical myelography followed by computerized tomography scanning assesses the status of the egress of the spinal nerves from the spinal cord in supraclavicular brachial plexus injuries. Magnetic resonance imaging of the brachial plexus and the cervical spine and angiography should be carried out for suspected cases of TOS and tumors.

Operative Approaches

An anterior operative approach is used in the majority of cases of brachial plexus trauma, including stretch, GSW and lacerations[12)]. The posterior subscapular approach with resection of the first rib is occasionally used for resection of tumors, GSWs of the lower roots and trunk and a majority of patients with TOS[2)]. These two approaches have been previously reviewed[9,10,14)].

Table 1. Traumatic supraclavicular plexus stretch injuries

Initial Loss of	Degree of	Postoperative Grades									
Function	of Loss	0	1	1–2	2	2–3	3	3–4	4	4–5	Totals
C5/C6/C7/C8/T1	C	21	8	15	29	62	40	20	13	0	208
C5/C6/C7	C	1	0	0	2	14	23	20	9	6	75
C5/C6	C	1	0	0	0	6	14	18	9	7	55
C8/T1	C	2	3	2	2	0	2	0	0	0	11
C8/T1	I	0	0	0	0	0	0	2	2	3	7
C6/C7/C8/T1	C	0	0	0	1	0	2	1	0	0	4
C5/C6/C7/C8	C	0	0	0	0	0	1	1	0	0	2
C7/C8/T1	C	0	0	0	0	1	1	0	0	0	2
C7/C8/T1	I	0	0	0	0	0	1	1	0	0	2
Total	4C/2I	25	11	17	34	83	84	63	33	16	366

C = complete; I = Incomplete (adopted with permission from J. Neurosurg 98:1005–1016, 2003)

Surgical Techniques

There are four surgical techniques used in the repair of brachial plexus injuries. The first is that of intraoperative nerve action potential(NAP) recording : a regenerating spinal nerve exhibits low-amplitude and slowconducting NAPs at 3 to 4 months postinjury, while flat NAPs are found in a non-regenerating nerve. A rapidlycond-

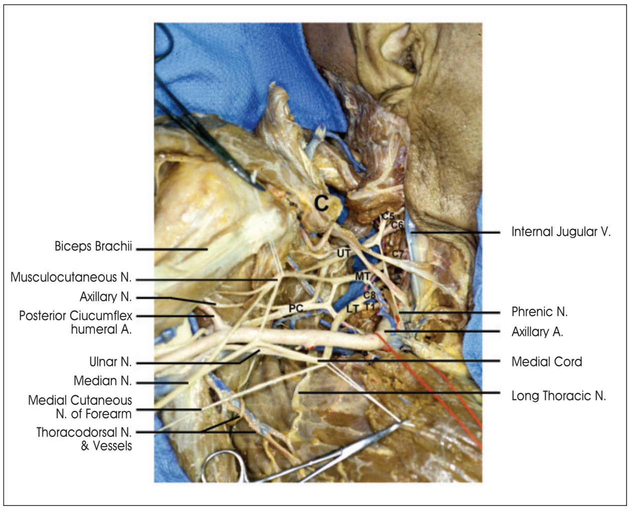

Fig. 2. This is the right infraclavicular brachial plexus viewed from medial to lateral (cadaveric dissection). The clavicle and pectoralis major muscle have been removed.

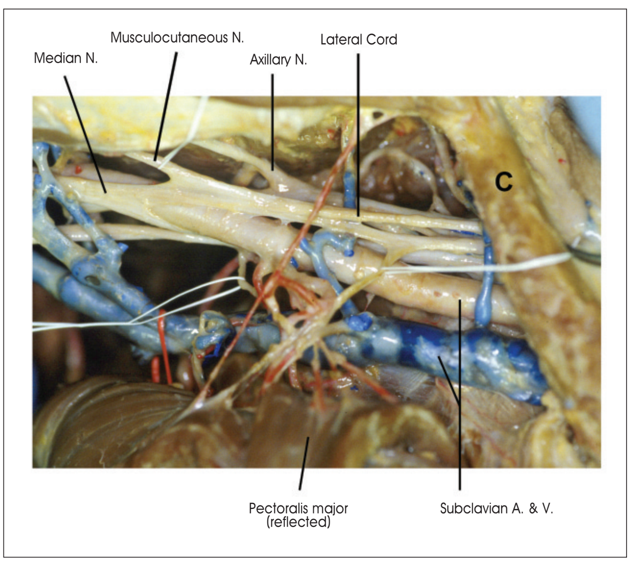

Fig. 3. A cadaveric dissection illustrating the subclavian vessels proximity to the infraclavicular plexus elements. This is the reason for the higher number of associated vascular injuries with infraclavicular brachial plexus injuries.

ucting, large amplitude NAP occurs if there is a preganglionic injury to the dorsal root. In this case the actual NAP is due to sensory fiber sparing distal to the dorsal root ganglion, in spite of 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, an NAP is unable to be recorded.

Neurolysis is a second technique used in the repair of brachial plexus injury and is performed if an intraoperative NAP indicates a regenerative NAP. The technique of external neurolysis is carried out using a No. 15 scalpel blade or Metzenbaum scissors. Nerve segments are freed circumferentially and in a proximal and distal direction from either side of the injured segment toward the segment.

If there is severe postganglionic damage to the extradural root or spinal nerve, or if there is both pre- and postganglionic damage and no NAP is recordable, resection of the spinal nerve and the more distal and involved plexus elements are performed. When NAP recordings are flat the spinal nerve or extradural root is sectioned back toward the dura. The spinal nerve is exposed proximally by removing bone around the element. If there is no electrical conduction and a short nerve gap is found or could be gained with minimal tension, post-resection end-to-end suture anastomosis repair is performed.

If fascicular structure is found, but there is a large interneural gap, an end-to-end repair is not possible. Sural autografts are then led out from that level to enable a grouped interfascicular repair. Grafts are also used for lengthy lesions in continuity without recordable NAPs, which are then resected and for retracted stumps of transected nerves, which cannot be approximated without tension.

A split-repair is performed when a portion of the element's cross-section exhibits more damage than the remainder of the element. The damaged segment is split away from the more normalappearing nerve segment and if no NAP is recorded across this damaged segment after it is split away, it is resected and repaired by graft. Excess scar tissue is removed from the segment to be spared, with care taken to not sacrifice the fascicular structure. Graft repair is not performed 1) if the fascicular structure from which to lead out grafts is not visualized; 2) in severely damaged or avulsed roots at an intradural level or 3) if the proximal extradural root or spinal nerve is scarred on cross-section and does not have a discernable fascicular structure

Traumatic Mechanisms of Injury and Results

Stretch/contusion injury

The most common lesion of the brachial plexus is stretch/contusion. These injuries usually result from motor vehicular accidents, especially those involving motorcycles, though sports injuries involving the plexus can also be responsible. The injury results from the head and neck being pushed in one direction and the shoulder and arm in another. Caudal traction of the shoulder and arm injures the upper roots (C5, C6), lateral traction, the C7 root and cranial traction the lower roots (C8, T1).

A period of conservative management of 3 to 4 months prior to operative exploration was favored[11)] in the Louisiana State

University Health Sciences Center(LSUHSC) series of outcomes of patients with 1,019 operative brachial plexus lesions evaluated between 1968 and 1998 analyzed by Kim and Kline et al.[6]. This was because early evidence of spontaneous recovery takes longer to manifest in cases of stretch injuries than it does in cases of GSWs, since lesions are longer in stretch injury[17].

In the LSUHSC series, of 1,019 injuries, there were 509 (49%) stretch/contusion injuries of which many had accompanying avulsions. These 509 injuries included 366 (72%) supraclavicular and 143 (28%) infraclavicular lesions. The stretch/contusion injuries were followed in number by brachial plexus GSWs (12%) and lacerations (7%). Nontraumatic injuries of the brachial plexus included tumors (16%) and TOS (16%).

Table 2. surgical outcomes for 143 infraclavicular stretch injuries*

Injury	No. of Elements/Mean Grade of Recovery			
	Neurolysis	Suture	Graft	Split Repair
Cord lesions				
lateral	12/4.5	3/4.3	6/3.8	3/4
medial	16/3.9	2/2.2	7/1.2	4/3.6
posterior	14/4.1	2/3.6	6/3.0	3/3.5
Cord–to–nerve lesions				
posterior to musculocutaneous	20/4.4	0/0	35/3.8	0/0
lateral to median	29/4.1	1/4	19/3	0/0
median to median	24/4.3	1/4	17/3	0/0
medial to ulnar	33/3.6	1/0	13/1.4	1/2.3
posterior to radial	29/4.1	1/0	3.2/1.4	1/2.3
posterior to axillary	28/4.7	1/3	48/3.5	1/4
Totals	205/4.2	12/2.3	183/2.8	15/3.6

No. = number *Results are given as total number of elements/number of elements recovering to a grade 3 or better (cited with permission from J. Neurosurg 98 : 1005–1016, 2003)

Table 3. Outcomes of surgery for 118 brachial plexus GSW injuries*

Type of Lesion	No. of Elements	Neurolysis	%	Suture	%	Graft	%
Lesions with complete loss	202	46/42	91%	21/14	67%	135/73	54%
Lesions with incomplete loss	91	82/78	95%	6/5	83%	3/2	67%
Total	293	128/120	94%	27/19	70%	138/75	54%

*Results are given as total number of elements/number of elements recovering to a grade 3 or better (cited with permission from J. Neurosurg 98 : 1005–1016, 2003)

Table 4. Outcomes of surgery for 71 brachial plexus lacerations

Factor	Elements in Continuity	Sharp Transection	Blunt Transection	Totals
No. of plexus cases	20	28	23	71
No. of plexus elements	57	83	61	201
Neurolysis	26/24	0/0	0/0	26/24 (92%)
Primary suture	0/0	31/25	0/0	31/25 (81%)
Secondary suture	9/7	12/8	5/3	26/18 (69%)
Secondary graft	22/17	40/21	56/25	118/63 (53%)
Total elements	57/48	83/54	61/28	201/130 (65%)

*Results are given as total number of elements/number of elements recovering to a grade 3 or better. Primary denotes repair within 72 hours after injury; secondary denotes delayed repair after several weeks (adapted with permission from J. Neurosurg 98 : 1005–1016, 2003)

Supraclavicular stretch/contusion injury

Supraclavicular stretch/contusion injuries can be subdivided into four patterns depending on spinal root injury level (Table 1).

In the Kim and Kline et al. article cited above[6] 366 supraclavicular stretch/contusion injuries were subcategorized into 1) C5-T1 nerve injuries (208 injuries, 57%) resulting in injury to 1,040 spinal nerves each of which were tested intraoperatively. This C5-T1 group was the largest and had the lowest spontaneous recovery rate (4%). Patients presented with a flail arm, i.e. total upper extremity paralysis.

In this C5-T1 group, 470 of 1,040 (45%) elements were found to have proximal damage not able to be repaired. Thirty-five patients had neurolysis of one or more plexus elements.

Direct graft repairs were performed on the remaining 570 (55%) spinal nerves. Graft repairs of two spinal nerves per patient were performed in 54 cases and three or more spinal nerves per patient were repaired in 76 cases. Nine patients had split-graft repair of the C5 or C6 nerve and its outflows.

Restoration of significant shoulder abduction and elbow flexion was obtained in 40% of cases and elbow extension in 30%, however, wrist or finger movement was seldom achieved. Much of the better functional grades were due to shoulder and upper-arm recovery rather than distal function. Only 35% gained a functional outcome of grade 3 or better.

The second group consisted of 2) 75 C5-C7 nerve injuries (20%). These resulted in weakness of a) the C5-C6 muscles, which include the supra- and infraspinatus, deltoid, biceps/brachioradialis and supinator muscles and in addition, weakness of b) the C7 muscles, which are the elbow, wrist and finger extensors. Loss of wrist and finger extension and weakness of the flexor digitorum profundi muscles varied due to dominance of the uninjured C8 nerve input to these muscles in some patients. The C5-C7 group had more roots avulsed than the C5-C6 group.

In 26 of 75 cases (35%) graft repair was performed with a graft from only one or two proximal spinal nerves. In 10 patients (13%) with C6 and C7 avulsions, direct graft repairs were led from C5 with a supplement from the descending cervical plexus. Recovery averaged only grade 2 to 3. In 10 cases (13%) of isolated C7 avulsions, direct graft repairs from C5 and C6

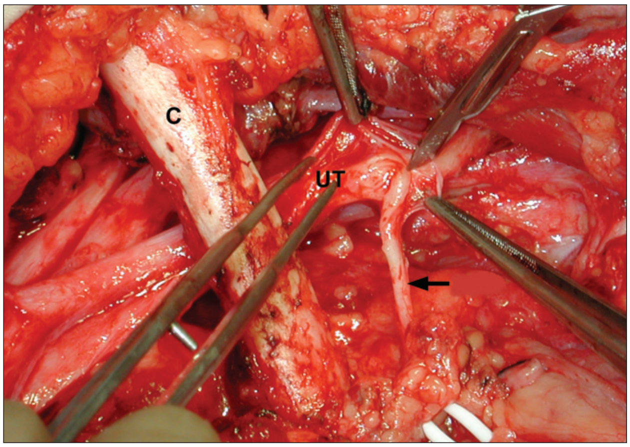

Fig. 4. A gunshot wound to the left brachial plexus is shown in this photograph taken in the operating room. Note that the injury mechanism is stretch contusion and it involves the upper trunk to suprascapular nerve (arrow) (UT = upper trunk).

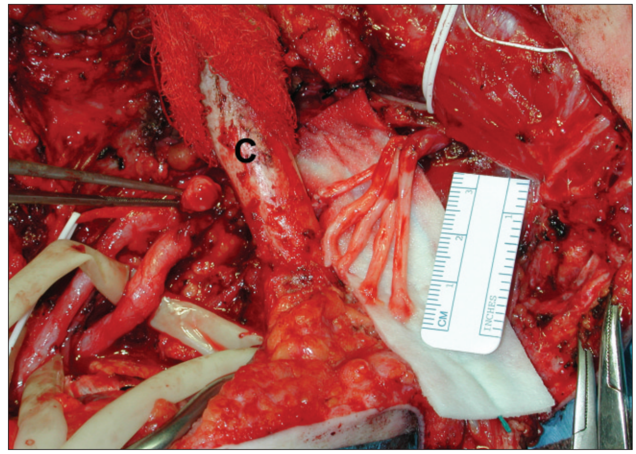

Fig. 5. An operative photograph of a contusion lesion due to a gunshot wound. The nerve action potential was negative, the lesion was resected and a 3 cm interfascicular graft was placed proximally to the C5 nerve root. The distal portion of the graft repair is shown being held by forceps prior to being sectioned back to healthy tissue of the lateral cord(C= clavicle).

to the anterior and posterior divisions of the upper and middle trunks resulted in an average recovery of grade 3. Six patients (8%) who had a C5 avulsion and received direct graft repairs to C6 and C7 achieved an average recovery of grade 3.5.

The technique of neurotization (nerve transfers) was integrated into the treatment of brachial plexus injuries for patients presenting in the years between 1999-2002. Thus, 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.

Another pattern of supraclavicular stretch/contusion injuries involved 3) C5-C6 nerve injuries, of which there were 55 lesions (15%). These patients presented with weakness of the C5-C6 muscle groups as defined above in 2a). Twelve patients underwent neurolysis due to a positive NAP.

Forty-three patients with C5 and C6 lesions required graft repairs. Of 43 graft repairs, 34 (79%) involved direct grafts leading out from both the C5 and C6 roots to the anterior and posterior divisions of the upper trunk. Nineteen patients recovered to grade 3, eight to grade 4 and seven patients to grades 3 to 4.

Five patients had an isolated C6 avulsion and underwent direct graft repair to the C5 nerve with a supplemental or nerve transfer from the descending cervical plexus. Outcomes in this group were grade 2 or 3. In recent years this group of patients has undergone medial pectoral branch transfers to the musculocutaneous nerve with improved results for the biceps muscles.

Two patients had a C5 avul-sion and underwent graft repairs to the C6 nerve with supplements from the descending cervical plexus resulting in a better recovery grade of 3 or 4. Several patients in this category had an anastomosis between the accessory and suprascapular nerve with improved results from the supraspinatus muscle. In the C5 and C6 group, return of elbow flexion via the biceps/brachialis muscle was always better than shoulder abduction by the deltoid and supraspinatus muscles.

There were 28 4) "other" injury patterns involving the C8-T1 or C7-T1 nerves (8%).

Infraclavicular stretch contusion injury

Infraclavicular stretch injuries can be subdivided into those that are at a 1) division or cord level and 2) cord-to-nerve level (Table 2). In the LSUHSC study,[6] 35 of 143 (24%) infraclavicular injuries resulted in injury to 78 elements at a division or cord level. Repair of lateral cord stretch injuries produced a mean grade of 4.5 for neurolysis, based on the presence of a positive NAP, 4.3 for sutures and 3.8 for grafts.

Medial cord stretch injuries underwent 29 repairs and these did not succeed as well. Neurolysis repair based on the presence of a

Table 5. Benign neural sheath tumors in the brachial plexus region (n=141)

	Schwannoma	Sporadic NF	NF−NF1	Totals
Supraclavicular brachial plexus	37	34	19	90
Infraclavicular brachial plexus	9	14	8	31
Axillary nerve	3	4	4	11
Musculocutaneous	3	2	1	6
Other	2	1	0	3
Totals	54	55	32	141

NF = neurofibroma; NF−NF1 = neurofibroma associated with neurofibromatosis type I. (With permission from Elsevier Saunders: Neurosurg Clin N Am 15 (2004) 177−192) positive NAP resulted in a mean grade of 3.9, suture repair, a mean grade of 2.2 and graft repairs, a mean grade of 1.2. The repair of posterior cord lesions required difficult dissections due to prior vascular repairs (Fig. 3). Twenty-five of these posterior cord lesions, however, did better than medial cord lesions. Neurolysis resulted in a mean grade of 4.1, suture an average grade of 3.6 and graft repair resulted in a mean grade of 3.

One-hundred patients had 337 injured plexus elements at a cord-to-nerve level. Mean outcomes for the lateral cord to its outflows were grade 4.2 for neurolysis, a grade 4 for sutures and a grade 3 for grafts. In patients with medial cord-to-ulnar nerve injuries (49 elements), 13 graft repairs resulted in poor outcomes, with a mean 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, 29 neurolysis procedures resulted in a mean grade of 4.1 and 32 graft repairs resulted in a mean grade of 2.7.

In the remaining 108 infraclavicular brachial plexus injuries, 78 of the 337 total injured plexus elements were posterior cord-to-axillary nerve injuries, 38 of 78 had isolated axillary nerve involvement, 11 were associated with suprascapular nerve injuries, 13 were associated with the posterior cord and 16 were associated with other lesions. Overall, the 28 neurolysis procedures in which intraoperative NAPs were recorded had a mean recovery grade of 4.7 and 48 graft repairs performed in this group produced a mean grade of 3.5. The remainder of the cord-to-nerve delineations are included in Table 2.

Gunshot wounds

Gunshot wounds most often produce lesions in continuity (Fig. 4), 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, which rarely injures nerves and shock wave and cavitation effects, which compress and stretch the nerve[19]. Low-velocity missile injuries tend to be associated with less damage to the brachial plexus and surrounding structures, while high-velocity injuries fail to recover spontaneously.

As in stretch/contusion injury, each plexus GSW injury must be evaluated by the element involved and not by the plexus as a whole using intraoperative stimulation and NAP recording to identify elements needing resection. Often associated vascular injuries warrant emergency repair,[8] since 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, 16 patients (30%) had associated vascular injuries that required emergent repair[19].

In the LSUHSC publication of 1,019 brachial injuries,[6] after stretch contusion injury, 118 GSWs of the brachial plexus represented 12% of the brachial plexus injuries. and resulted in injury to 293 plexus elements (Table 3).

A very high percentage (92%) of elements injured by GSWs were found to be intact at operation, even with complete loss distal to the lesion. 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 293 "in continuity" elements that were explored and evaluated, 120 had recordable NAPs. These elements underwent neurolysis and function improved to grade 3 or better in 94% of these cases. Elements that did not have early evidence of regeneration usually required repair. Thus, 156 (52%) of the 202 suspected completely injured elements required resection and repair as indicated by intraoperative NAP evaluation.

Repairs were relatively effective for the upper trunk and C5-6 nerve roots and for lateral and posterior cords and their outflows. Acceptable results were achieved by grafts in 73 of 135 (54%) cases in which there was complete loss and by suture in 14 of 21 (67%) 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 inches) (Fig. 5). Recovery occured in severe C-8, T1, 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.

Lacerations

In our LSUHSC series, 71 lacerations resulted in 7% of the 1,019 brachial plexus injuries[6]. Laceration injury can either transect a portion of the plexus, which is the most common presentation or can lacerate the entire brachial plexus. As with GSWs to the brachial plexus, laceration injuries can also result from sharp lacerations due to knives or glass, or blunt transections due to automobile metal, fan and motor blades, chain saws or animal bites.

Laceration injuries are associated with vascular injury, which is suspected either clinically or proven angiographically. Vascular injuries in the cases presented in the Kim et al.[6] article included transection of major vessels, either partial or complete and hematomas. Pseudoaneurysm or arteriovenous fistula can also occur, but were not seen in the LSUHSC series.

If lacerations are sharp, urgent repair should be carried especially if loss of function is complete in the distribution of one or more elements. Early intervention is also indicated for increasing neurological deficit, which can be associated with progressive pain due to a hematoma, arteriovenous fistula or pseudoaneurysm. If the laceration is blunt, the nerve is "tacked" to adjacent planes to lessen retraction and the requisite need for graft repair and repaired secondarily at 2 to 3 weeks. Delay of repair for blunt injuries permits the damage in each stump to delimit itself.

Seventy-one plexus lacerations were due to either sharp or blunt lacerations (Table 4). Sharp transections accounted for injuries to 83 plexus elements and blunt transections injured 61 plexus elements. 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. Twenty-six elements associated with a positive NAP across the lesion were treated with neurolysis : 24 (92%) 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 and in seven (78%) of these cases the elements recovered. Graft repairs were performed on 22 other elements, 17 (77%) of which recovered. Grade 3 or better levels were achieved in 48 (84%) of the 57 involved elements.

When 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 transitions 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%.

Nontraumatic Mechanisms of Injury

Tumors and thoracic outlet syndrome are two nontraumatic mechanisms of injury to the brachial plexus. These resulted in 16% each of brachial plexus injuries in the Kim and Kline et al study quoted above[6].

Tumors

Tumors of the brachial plexus include those derived from the neural sheath and those that are derived from non-neural sheath tissues. Schwannoma and neurofibromas are the two major types of neural-sheath tumors. Neurofibromas are categorized as a solitary type or as neurofibromas associated with neurofibromatosis type 1 (NF1).

In a recent review of neural and non-neural sheath tumors managed at LSUHSC and published by Kim et al.[7] there were 141 benign brachial plexus neural sheath tumors evaluated. Of these there were 54 (38%) schwannomas and 87 (62%) neurofibromas of which there were 55 (63%) solitary neurofibromas and 32 (37%) neurofibromas associated with NF1 (Table 5). Of the malignant peripheral neural sheath tumors (MPNSTs) in this series, 22 of 39 (71%) involved the brachial plexus.

Of 54 patients who underwent surgery for schwannomas, 52 (96%) presented with a palpable mass and all but one experienced dysesthesias 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 with a mean age of 38.3 years, who had solitary neurofibromas of the plexus without NF1 underwent tumor resection surgery. The male/female ratio was eight : seven. All tumors in this group were excised completely. Of the 55 patients, 31 (56%) had intact function preoperatively. Of these, 23 (42%) maintained normal function whereas eight (15%) experienced some degree of postoperative weakness. Most of the 32 patients with tumors (mean age = 26.2 years) associated with NF1 underwent surgery for palliative reasons. The male/female ratio in this subgroup was seven : nine. Graft repair was attempted if loss of function was severe. This was not feasible, however, when there was extensive tumor involvement along lengthy segments of the elements. When a very large tumor was found, resection of 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.

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 for these 20 patients at presentation was 45 years. Fourteen underwent local resections and six underwent local resections with margins. Subsequently, 6 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.

Regarding non-neural sheath tumors of the brachial plexus, of 111 involving brachial plexus, upper and lower extremities and pelvic plexus, there were 33 (30%) brachial plexus non-neural sheath tumors. These brachial plexus tumors included 6 desmoid tumors, 4 ganglion cysts of the suprascapular nerve at the brachial plexus, 3 lipomas (two of which involved the brachial plexus and one each of the musculocutaneous and axillary nerves at the brachial plexus), 3 each of local hypertrophy neuropathy and ganglioneuromas, 2 myositis ossificans, meningiomas and cystic hygromas, myoblastoma or granular cell tumors, triton tumor and 1 lymphangioma. In the malignant category, of 35 tumors involving brachial plexus, upper and lower extremities and pelvic plexus a majority of 31 (89%) involved the brachial plexus region.

Thoracic outlet syndrome

TOS results from compression of nerves and vessels supplying the upper limb by soft tissue or bony 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[5].

In the LSUHSC experience6 160 operations were performed on 151 patients by using either an anterior (62 patients) or posterior (98 patients) subscapular approach. Unilateral symptoms were present in 142 patients and nine others had bilateral symptoms requiring bilateral surgery. The patients ranged in age from 11 to 70 years. More than half of the patients were between 30 to 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 either 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 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 did loss of function in the intrinsic muscles of the hand, although a few patients experienced improved function of the intrinsic muscles by one or two grades.

Obstetrical brachial plexus injury

Birth palsy is another type of brachial plexus injury. The most common obstetrical injury is that of Erb's palsy, which is due to a C5-C6 innervated upper trunk injury[1,16]. Hallmarks of an Erb's palsy are an internally-rotated, adducted shoulder, an extended or slightly-flexed elbow, a pronated forearm and a flexed wrist. The muscles involved include the deltoid, supraspinatus, biceps and brachioradialis, supinator and medial shoulder rotators. If only C5 is involved there is no anesthesia.

Klumpke's palsy, which is less common than Erb's palsy, occurs as a birth injury in which the arm is abducted forcibly over the head. A sharp decline in vaginal breech births has decreased the risk of the hyperabduction of the fetal arms. A Klumpke's palsy results in atrophic paralysis of the forearm, small muscles of the hand and flexors of the fingers and thumb. Decreased sensation is found on the ulnar side of the arm, forearm and hand and paralysis of the cervical sympathetic system occurs, as well.

The incidence of obstetrical brachial plexus injury was documented by Ladfors et al. Of 1, 213, 987 births, a birth BPI was found in 2,399 neonates (0.18%)[13]. Variables associated with brachial plexus injury were shown to include fetal macrosomia, shoulder dystocia, breech delivery, operative vaginal delivery, maternal diabetes mellitus, secondary arrest of dilatation and epidural anesthesia. Other risk factors include maternal obesity or excessive weight gain and the use of forceps during delivery[20]. An increased birth weight, especially more than 4kg has been implicated by Giddins, et al.[4]. A persistent occiput posterior position has also been associated with an increase incidence of Erb palsy. Gherman, et al.[3] suggested that brachial plexus palsies in infants may precede the delivery itself and occur in utero. This was supported by Ouzounian, et al.[18] in which a review of several cases of permanent Erb's palsies showed no identifiable risk factors for injury.

The timing of surgery is controversial. Al-Qattan recommends operating at 4 months of age if the indication for Erb's palsy brachial plexus surgery was that of absence of elbow flexion against gravity[1].

At LSUHSC, a 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 C5, C6 and C7 and the upper and middle trunks are important. The majority of patients at LSUHSC have been managed without surgery[9]. At the present, 185 children with birth palsies at LSUHSC have been evaluated and surgery had been performed in only 21.

Summary

The brachial plexus can be injured by multiple mechanisms. Traumatic mechanisms include stretch/contusion which is the most frequently encountered, followed by GSWs and lacerations. Nontraumatic injury such as tumors and various etiologies of TOS can also result in brachial plexus lesions. Obstetric birth palsies are yet another mechanism resulting in brachial plexus injury in newborns.

The brachial plexus is usually repaired by an anterior approach, though a posterior approach is occasionally used to resect tumors, lower root and trunk GSWs and patients with TOS. Four surgical techniques are used for the repair of brachial plexus lesions. These include intraoperative NAP testing, neurolysis, anastomotic end-to-end suture repair, and graft repair including split-graft repairs for elements that are partially injured.

For stretch/contusion injuries a period of conservative management of 3 to 4 months is undertaken prior to operative exploration, since evidence of spontaneous recovery takes longer to manifest in stretch/contusion injury due to usually longer lesions. In GSWs some lesions that are in continuity recover spontaneously, but others display no signs of reversal or reinnervation after several months at which time exploration and intraoperative NAP recording should be performed. Often associated vascular injury, however, will warrant emergency repair. If lacerations are sharp, urgent repair should be carried especially if loss of function is complete in the distribution of one or more elements. If the laceration is blunt, the nerve is "tacked" to adjacent planes and repaired secondarily at 2 to 3 weeks.

The majority of cases of obstetrical palsies were managed without surgery (21 of 185, 11%) and those that underwent operations usually had a complete loss of function persisting for a period of 7 to 10 months in the distribution of one or more plexus elements that can be helped by operation.

Functional outcomes were best for injuries that resulted in a lesion in continuity and positive NAP. Results after repair by suture or grafts were good for injuries to C5, C6 and C7; 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. Favorable outcomes can be achieved in tumors and some TOS cases if patients are carefully selected.

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