Restoration of Elbow Flexion after Brachial Plexus Injury: The Role of Nerve and Muscle Transfers

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Learning Objectives: After studying this article, the participant should be able to: 1. Perform appropriate diagnostic evaluation of a brachial plexus injury. 2. Define goals of treatment in brachial plexus injuries resulting in loss of elbow flexion. 3. Identify appropriate nerves and muscles for transfer procedures to regain elbow flexion. 4. Make an appropriate selection of surgical procedures to achieve elbow flexion.

Brachial plexus trauma results in a variable loss of upper extremity function. The restoration of this function requires elbow flexion of adequate strength and range of motion. A proper evaluation of brachial plexus lesions is a prerequisite to any reconstructive procedure, and appropriate guidelines are presented. One option for restoring elbow flexion is a nerve transfer. The best results with this procedure are obtained in young patients treated within 6 months of injury. Another option is a free or pedicled muscle transfer, which should be considered in older patients or patients treated more than 6 months after an injury. Muscle transfers may also be used to augment the results of nerve transfer procedures. Choices and clinical results of donor nerves and muscle for transfer are discussed, and an algorithm for treatment is presented. (Plast. Reconstr. Surg. 106: 1348, 2000.)

Although uncommon, brachial plexus trauma may be devastating because of the resulting severe upper extremity functional impairment. The difficulty in treating these injuries is compounded by the complex and variable anatomy of the brachial plexus, the long time intervals required for resolution after injury or improvement after surgical intervention, the need for a long-term patient-physician commitment, and the need for a motivated patient to proceed with the difficult rehabilitation. Goals of treatment depend on the extent of remaining function and on the nature of the injury itself. When a flail arm is present, the most important function to regain is elbow flexion. This review will cover the common patterns of nonobstetric brachial plexus injuries, offer options for nerve and muscle transfer reconstructive procedures, and provide treatment recommendations for elbow reanimation on the basis of an analysis of published data.

Patient Characteristics

Most brachial plexus injuries are a result of high velocity, traction-type trauma, as seen in motor vehicle collisions, especially motorcycle and motor scooter accidents. The victims are usually young men who are unskilled or just starting manual labor careers and, therefore, the economic costs of these injuries is high. One-quarter to one-third of those with severe injuries will regain minimal or no function. In the largest series of brachial plexus reconstructions in North America, good or excellent results were obtained in 75 percent of suprascapular reconstructions, 48 percent of biceps reconstructions, 30 percent of triceps reconstructions, 35 percent of finger-flexion reconstructions, and 15 percent of finger-extension reconstructions.¹

Patterns of Injury

Figure 1 diagrams the brachial plexus, which consists of contributions from the C5, C6, C7,
C8, and T1 nerve roots, with variable contribution from the C4 and T2 roots, and provides motor and sensory innervation to the upper extremity. Large reviews of the patterns of injury show that 75 percent of the lesions are supraclavicular at the root level, whereas the remaining 25 percent are infraclavicular. Of the supraclavicular lesions, 75 to 80 percent involve the plexus from C5 to T1, with the most common pattern being a C5-C6 rupture and a C7-C8-T1 root avulsion from the spinal cord. A total of 20 to 25 percent of supraclavicular injuries involve C5-C6 or C5-C6-C7 and 2 to 3 percent involve C8-T1. Muscles affected by each pattern of injury, resultant functional loss, and reconstructive goals are listed in Table I. When the C5 and C6 nerve roots are involved, the goal is to reproduce the elbow

<table>
<thead>
<tr>
<th>Nerve Roots</th>
<th>Muscles Affected</th>
<th>Functional Loss</th>
<th>Reconstructive Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>C5-C6</td>
<td>Subscapularis, subclavius, deltoideus, supraspinatus, infraspinatus, biceps brachialis, coracobrachialis, and brachioradialis (± radial wrist extensors and cavicular pectoralis major)</td>
<td>Shoulder rotation, abduction and forward flexion, and elbow flexion (± wrist extension)</td>
<td>Stable shoulder and elbow flexion</td>
</tr>
<tr>
<td>C5-C6-C7</td>
<td>Same as C5-C6 and serratus anterior, extensor carpi radialis longus and brevis, flexor carpi radialis, extensor digitorum communis, extensor pollicis longus, extensor pollicis brevis, and abductor pollicis longus</td>
<td>Same as C5-C6 and extension of elbow wrist, fingers, and thumb (presence of winged scapula)</td>
<td>Stable shoulder, elbow flexion, and wrist extension</td>
</tr>
<tr>
<td>C7-C8-T1</td>
<td>Latissimus dorsi, extensor digitorum communis, extensor pollicis longus flexor digitorum superficialis and profundus, flexor pollicis longus, and all intrinsic hand muscles</td>
<td>Finger extension, finger and thumb flexion, and intrinsic hand functions</td>
<td>Wrist extension and thumb pinch</td>
</tr>
<tr>
<td>C5-C6-C7-C8-T1</td>
<td>All above muscles</td>
<td>All above functions</td>
<td>Elbow flexion</td>
</tr>
</tbody>
</table>

Fig. 1. Anatomy of the brachial plexus.
flexion normally provided by the biceps muscle, which is innervated by the musculocutaneous nerve from the C5 and C6 roots.

**CLINICAL EVALUATION**

A clinical examination of the patient with a brachial plexus injury should identify the affected muscles and look for signs of root avulsion and nerve regeneration. A winged scapula with an intact spinal accessory nerve is highly suggestive of a C5-C6-C7 avulsion, whereas the presence of Horner’s syndrome (enophthalmos, myosis, ptosis, and absence of facial sweating on the affected side) suggests a cervical or T1 root avulsion and interruption of sympathetic innervation. A sensory-sweating dissociation in an anesthetic and flail arm also suggests root avulsion. In these cases, recovery cannot be expected, and surgical exploration is warranted. A functioning supraspinatus muscle predicts that C5 is not avulsed. A supraclavicular Tinel’s sign suggests a connection between the involved nerve and the central nervous system and, therefore, recovery of the affected nerve may occur. A paralyzed diaphragm, as determined by inspiratory/expiratory chest x-rays or fluoroscopic studies, suggests a high plexus lesion.

Upper extremity angiograms should be used in patients with a history of significant vascular injury, especially if free tissue transfer is anticipated. Shoulder and arm muscles should be tested individually and graded using the following system:

- **M0**: No contraction
- **M1**: Flicker or trace of contraction
- **M2**: Active movement with gravity eliminated
- **M3**: Active movement against gravity
- **M4**: Active movement against resistance
- **M5**: Normal movement

Muscles must be grade M4 or M5 to be useful for transfer because one grade of strength is lost after transfer. Muscles with uncontrolled spasticity should not be transferred. A datasheet shown in Figure 2 is useful for documenting functional recovery after serial examinations and in identifying the location of lesions in the brachial plexus.

Further clinical studies include electrodiagnostics, which consist of an electromyogram (which should be done at least 3 weeks after injury) and the determination of nerve conduction velocities. Imaging studies traditionally consisted of myelography and, later, computed tomography myelography; however, magnetic resonance imaging is noninvasive and offers multiplanar imaging without shoulder artifact. The decision of when to explore an injured brachial plexus depends on these clinical findings, with functional recovery being looked for during serial examinations. Figure 3 shows an algorithm proposed by Brunelli and Brunelli, which is based on their extensive experience with these injuries.

**GOALS OF TREATMENT**

The goals of treatment are to restore grade M4 or M4+ elbow flexion with a range of motion that will allow the hand to reach the face. Although many studies report obtaining M5 elbow flexion, it is unlikely that full strength is ever achieved. Realistically, M4+ strength is the best one can expect from a reconstructive procedure. The resulting function of elbow flexion must outweigh the deficits caused by transferring functional nerves or muscles. Furthermore, there should be a reasonable time to recovery of useful function. To prevent dissipation of elbow flexion strength, the shoulder must be stable. This can be achieved by a nerve transfer of the spinal accessory or phrenic nerves, arthrodesis, or tendon transfers. After adequate elbow flexion has been established, procedures to allow wrist and finger extension may follow. Occasionally, active elbow extension or wrist and finger flexion can also be achieved.

**NERVE REPAIR AND RECONSTRUCTION PROCEDURES**

Extremity reanimation may be achieved by nerve repair or by nerve transfer, which is the transfer of a nerve in continuity with the spinal cord to the end of a nerve that has lost its spinal cord connection. This is different from neurotization, which is the process of reinnervating a muscle by placing a functional nerve directly in contact with muscle tissue. When dealing with nerve ruptures, neurolysis is the simplest method of repair. If a significant nerve gap exists or if extensive scarring and fibrosis are present, nerve grafts should be used to bridge the gap or bypass the fibrotic area. Common sources of grafts include the sural and medial cutaneous nerves and, in cases of C8 and T1 avulsion, the ulnar nerve may also be used. Results tend to be better in grafts placed in the upper trunk than in the lower trunk. If a significant neuroma is present at the site of injury, neurolysis or neuroma
excision and nerve grafting is indicated, depending on the amount of functional nerve fibers.

Nerve root avulsions must be treated by nerve or muscle transfer procedures. In these cases, it is important to anticipate the functional result and to keep in mind the resulting deficit from the donor nerve or muscle. Furthermore, studies of nerve and muscle transfer outcomes must be critically examined because some positive results may be due to spontaneous recovery by alternate neural pathways. Figure 4 shows the ideal donors for nerve transfer, which should be in proximity to the brachial plexus.

Useful donor nerves are listed in Table II with their corresponding number of myelinated axons. In comparison, the numbers of myelinated axons in the recipient nerves are listed in Table III. It is clear that most axons in a peripheral nerve will not be functional after a single donor nerve transfer because of the unfavorable ratio of donor to recipient axons. Fortunately, a simple action, such as elbow flexion by the biceps, requires only hundreds of functioning axons to be useful. Complex actions, such as those of the intrinsic muscles, require thousands of axons, and useful results should not be expected after nerve transfers to these muscles. In a review of 107
cases, Millesi\textsuperscript{15} found useful arm function was obtained more often with neurolysis (72 percent), nerve grafts (70 percent), and neurorhaphy (67 percent) than with nerve transfers (41 percent).

**Intercostal Nerve Transfer**

Intercostal nerve transfer is one of the more common methods of reanimating the arm. Typically, the third, fourth, and fifth intercostal nerves are used; however, up to seven unilateral intercostal nerves have been used.\textsuperscript{16} When possible, the fourth intercostal nerve should be spared in women. Candidates for this procedure should have no history of rib fractures, thoracotomies, or chest tube placement in the potential donor nerve region. Electromyograms should be performed on intercostal nerves adjacent to previously fractured ribs to assure adequate function.\textsuperscript{1}

The highest content of motor nerves can be found just distal to the lateral cutaneous branch. Sensory reinnervation may be achieved by coapting the intercostal nerve sensory axons, which are located in the superior portion of the nerve, with the sensory axons of the musculocutaneous nerve, which are located in the superior and inferior poles of the nerve. The intercostal nerve motor fibers, which run in the inferior portion of the nerve, are coapted to the motor fibers located in the middle of the musculocutaneous nerve.\textsuperscript{17} Several large studies with a combined total of 377 patients treated by intercostal nerve transfer found that 46 percent of patients achieved grade M4 or M5 elbow flexion.\textsuperscript{17–23}

Additionally, Millesi\textsuperscript{24} found intercostal nerve transfers were more likely to have a useful result when the spinal accessory nerve was used to stabilize the shoulder by nerve transfer to the axillary or suprascapular nerves. Nagano et al.\textsuperscript{18} discovered that results were better when patients were younger than 40 years old and nerve transfer was undertaken within 6 months.

### TABLE II

| Potential Donor Nerves and Number of Myelinated Axons\textsuperscript{13} |
|-----------------------------|-------------------|
| Donor Nerve                 | Myelinated Axons  |
| Intercostal                 | 1300              |
| Cervical plexus motors      | 4000              |
| Spinal accessory            | 1700              |
| Long thoracic               | 1600              |
| Phrenic                     | 800               |
| C7                          | 24,000            |
| Ulnar (partial)             | 1600              |

### TABLE III

| Number of Myelinated Axons in Nerves of the Upper Extremity\textsuperscript{13} |
|-----------------------------|-------------------|
| Root/Nerve                  | Myelinated Axons  |
| Brachial plexus             | 100,000 to 160,000|
| C5-T1 (each root)           | 7000 to 41,000    |
| Axillary                    | 6500              |
| Musculocutaneous            | 6000              |
| Median                      | 18,000            |
| Ulnar                       | 16,000            |
| Radial                      | 19,000            |
of injury. Generally, only two or three intercostal nerves are needed to achieve elbow flexion, and nerve grafts should be avoided. If after appropriate follow-up elbow flexion is grade M3 or less, a muscle transfer procedure may be used to supplement the biceps. In less than 10 percent of patients, uncontrolled elbow flexion was reported with coughing, sneezing, or yawning, but none had a loss of pulmonary function.\(^2^5\)

**Spinal Accessory Nerve Transfer**

The spinal accessory nerve is another potential donor to achieve elbow flexion. The segment distal to the trapezius ramus is used to preserve sternocleidomastoid and trapezius function. Advantages include its sole function as a motor nerve and similar functional relationship with the musculocutaneous nerve. However, its use does require a nerve graft and, when needed, it is best saved for shoulder stabilization by nerve transfer. Songcharoen et al.\(^2^6\) showed good results when nerve transfer was undertaken within 6 to 9 months of injury and when patients were younger than 40 years old. Kawai et al.\(^2^1\) compared spinal accessory and intercostal nerve transfers for elbow flexion and found strength was greater than M3 in 44 and 42 percent of patients, respectively. In a prospective randomized trial, Waikakul et al.\(^2^5\) found very good or good power in 83 percent of patients who underwent spinal accessory nerve transfers using sural nerve grafts compared with 64 percent of those who had a transfer of three intercostal nerves without nerve grafts. However, the later group had earlier evidence of motor reinnervation, improvement in protective sensation, and a reduction in arm pain.

**Phrenic Nerve Transfer**

Despite concerns of decreased pulmonary function, the phrenic nerve has been successfully transferred. Gu and Ma\(^2^7\) found elbow flexion of grade M4 or M5 in 49 percent of their 49 patients. Although pulmonary capacity was decreased for 1 year after surgery, this normalized by 2 years. No respiratory complications were seen, even when intercostal nerves were also used.

**Cervical Plexus Transfer**

Up to four of the motor branches from the cervical plexus may be used for nerve transfer.\(^2^8\) Nerve grafts are required, and results are unpredictable when used alone; therefore, it is recommended that the spinal accessory or phrenic nerve be used in combination with cervical plexus nerve transfer to achieve better results.\(^1^2\)

**Hypoglossal Nerve Transfer**

An infrequent donor is the hypoglossal nerve. Disadvantages include the need for a nerve graft and the problem of the innervated muscle being activated during eating.\(^1^2\) Narakash\(^2^9\) cautions that there are no convincing reports that the functional donor deficit is insignificant.

**C7 Spinal Nerve Transfer**

Because the C7 spinal nerve may be sacrificed without significant loss of function, it is a reasonable donor for transfer.\(^1^2,3^0\) Often, the contralateral nerve is used.

**Partial Ulnar Nerve Transfer**

Oberlin et al.\(^3^1\) recently reported using a 10 percent cross-sectional area of the ulnar nerve in performing a two fascicle coaptation to branches of the musculocutaneous nerve in four patients. Three patients achieved M4 elbow flexion, whereas the fourth patient had M3 flexion by 9 months after surgery. Careful testing revealed no loss in ulnar nerve motor or sensory function.

**Muscle Transfer Procedures**

The local and distant muscles that may be transferred and used to provide elbow flexion include the following: flexor-pronator mass, pectoralis major, pectoralis minor, latissimus dorsi, triceps, and sternocleidomastoid and the gracilis, rectus femoris, and latissimus dorsi as free muscle transfers. This may be done alone or in combination with a nerve transfer procedure. Unlike nerve transfers, in which the original elbow flexor, the biceps muscle, is reactivated, muscle transfer procedures alter the biomechanics of elbow flexion. Therefore, at least M4 strength and the creation of at least 90 to 100 degrees of elbow flexion are needed to provide useful function.

**Steindler Flexorplasty**

A commonly used muscle transfer procedure for elbow reanimation is the flexorplasty, as originally described by Steindler.\(^3^2\) The procedure involves transfer of the flexor pronator mass (pronator teres, flexor carpi radialis,
flexor carpi ulnaris, palmaris longus, and flexor digitorum superficialis) from its insertion on the medial epicondyle to a point 4 to 6 cm more proximal on the humerus. An electromyogram study is recommended first to evaluate flexor digitorum superficialis and flexor carpi radialis muscle function. The flexorplasty may be technically easier if it is done before shoulder fusion (when this is needed). Generally, 1 to 2 kg of lift is achieved. This procedure is better at increasing elbow strength from M2 to M3 or M4 than from M0 or M1 to M3.

Brunelli et al. modified Steindler’s procedure by not including the flexor digitorum superficialis in an effort to avoid hand pronation and finger flexion during active elbow flexion. With this modification, 81 percent of 32 patients were able to lift 2 kg or more, and 56 percent had greater than 120 degrees of elbow flexion. A dramatic increase in the overall results of the flexorplasty can be achieved by performing additional tendon transfers for wrist and finger extension.

Pectoralis Major Transfer

The sternocostal portion of the pectoralis major muscle may be transferred and inserted to the biceps tendon by way of a fascia lata interposition graft. A stable shoulder is a prerequisite to prevent dissipation of power. This procedure may have better functional results than a flexorplasty, but the ability to hold objects against the body may be lost. In Brooks and Seddon’s report, all patients achieved at least 90 degrees of flexion and M3 or M4 strength.

Pectoralis Minor Transfer

There are few reports on the use of the pectoralis minor for elbow reanimation. It is suggested for C5-C6 palsy and provides M3 strength without donor functional loss. This transfer has been used to supplement a flexorplasty when initial elbow flexion is less than M2.

Latissimus Dorsi Transfer

The powerful latissimus dorsi muscle can provide more lift strength than a flexorplasty, but cortical retraining may be more difficult. Because of its C5-C6-C7 innervation, muscle strength must be assessed before transfer. Monneim and Omer could achieve only 65 to 115 degrees of flexion in their patients, whereas Hirayama et al. had 2 of 6 patients who could raise their hands to their mouths. Berger and Brenner found the maximal strength in elbow flexion for unipolar and bipolar latissimus dorsi transfers was 10 to 15 kg and 5 to 8 kg, respectively.

Triceps Transfer

Good strength is obtained from a triceps muscle transfer, but active elbow extension is lost and a flexion contracture may occur. Hoang et al.’s experience with 7 patients showed the achievement of 90 to 140 degrees of flexion, and 5 patients could bring their hands to their mouths. Alnot suggests this transfer for C5-C6 palsy when elbow flexion is M0.

Sternocleidomastoid Transfer

Although excellent results were reported with the sternocleidomastoid muscle transfer, it is no longer used because of the resultant neck deformity and the need for grotesque facial and neck manipulations to achieve flexion.

Free Muscle Transfer

In cases of delayed nerve reconstruction with target muscle atrophy and motor endplate degeneration, a free gracilis, rectus femoris, or contralateral latissimus dorsi muscle transfer is useful. Other indications include injury to the flexor muscle mass, lack of local donor muscles, and as a salvage procedure in complete brachial plexus avulsions or in failures of nerve transfer. Chuang et al. achieved M4 strength in 25 of 31 patients who had two or three intercostal nerve transfers to a free gracilis muscle transfer; however, this strength was not achieved in four patients who had spinal accessory nerve transfers with nerve grafts to the free gracilis muscle. Akasaka et al.’s experience with free rectus femoris transfer innervated by two intercostal nerves yielded four patients with M4 and four patients with M3 strength out of 11 patients. Berger and Brenner also used free unipolar and bipolar latissimus dorsi transfers and achieved 2 to 4 kg and 1 to 2 kg of strength in elbow flexion, respectively.

Comparisons of Muscle Transfer Procedures

Marshall et al. reported 19 of their 23 patients had good or fair results with a flexorplasty, and their best elbow flexion was 130 degrees. All six patients with latissimus dorsi and all five with triceps transfer had good or
fair results, with the best flexion being 130 and 120 degrees, respectively. Only 6 of the 11 patients who had pectoralis major transfers had good or fair results; their best flexion was 120 degrees. Although all patients with latissimus dorsi and triceps transfers achieved greater than 90 degrees of elbow flexion, only 74 percent of those who had flexorplasties and 55 percent of those with pectoralis major transfers reached this goal. A lack of shoulder stabilization was cited as the cause of poor results in these muscle transfers.

Chuang et al.\textsuperscript{44} found about half of their patients who had a flexorplasty or latissimus dorsi or free gracilis transfer could achieve greater than M3 strength, whereas all flexorplasty patients who underwent the procedure after previous unsatisfactory nerve or muscle transfers achieved this goal.

In a large series, Berger and Brenner\textsuperscript{39} demonstrated that the latissimus dorsi transfer provided the strongest force of lift; this was followed by the triceps transfer and then the flexorplasty. Eggers et al.\textsuperscript{45} also found the latissimus dorsi transfer was stronger than the flexorplasty, but both yielded at least M4 strength. The flexorplasty, however, had a lesser degree of elbow flexion. When the flexorplasty was compared with a pectoralis major transfer, Beaton et al.\textsuperscript{46} found no statistical difference in function, strength, range of motion, or activities of daily living in their patients.

**Combined Treatment: Nerve and Muscle Transfers**

Various combinations of nerve and muscle transfers have been proposed. Berger et al.\textsuperscript{47} suggest an initial nerve transfer procedure supplemented at least 1 year later by a triceps transfer or flexorplasty to achieve elbow flexion. Doi et al.\textsuperscript{48} used latissimus dorsi transfers for elbow flexion together with nerve transfers for wrist and finger extension. Alnot\textsuperscript{36} reported good results by adding muscle transfers to nerve graft and neurolysis procedures, either concurrently or as a secondary procedure.

**Treatment Recommendations**

On the basis of the expected outcomes of the many nerve and muscle transfer procedures, the following recommendations are offered to help guide treatment and achieve useful elbow flexion. In cases of C5-C6 rupture or severe traction injury (Fig. 5), the nerve root is intact and so treatment should be directed at the nerve lesion. Primary neurorrhaphy is performed when possible, and nerve grafts are reserved for extensive scarring and fibrosis. Neuromas may be treated by neurolysis or neuroma excision followed by nerve grafting.

If minimal or no improvement occurs after an appropriate waiting period, a muscle transfer is indicated. If elbow flexion is less than M2, a triceps transfer is preferred or, alternatively, a flexorplasty combined with a pectoralis minor transfer. If elbow flexion is M2 or greater, a flexorplasty alone should provide adequate strength. Other options include a pectoralis major or latissimus dorsi transfer or a free muscle transfer if the previous muscles are not available or do not have at least M4 strength.

In cases of C5-C6 avulsion (Fig. 6), a nerve transfer may be attempted. The intercostal nerve should be considered first and then the ipsilateral and contralateral C7 nerve root or the ulnar nerve in a partial fashion. The spinal accessory and phrenic nerves should be re-
served for shoulder stabilization, if needed. If at least M4 strength is not achieved, a flexor-plasty or triceps transfer (if C7 is not involved) may be added; a free muscle transfer may be done if local muscles are unavailable. Nerve transfer may also be attempted if no muscles are available for transfer. However, if more than 6 months have passed since the time of injury, if the patient is older than 50 to 40 years, or if significant biceps muscle atrophy is present, elbow flexion is best achieved by proceeding directly to a muscle transfer procedure, because nerve transfer procedures are unlikely to provide useful function. If local muscles for transfer have less than M4 strength, a free muscle transfer is necessary.

TREATMENT HORIZONS

Nerve root avulsions were originally thought to be irreparable injuries because reimplanting the avulsed root in the spinal cord was not considered possible. After much research, Carlstedt et al. challenged this notion. In a single patient, the C6 and C7 nerve roots were reimplanted in the spinal cord and, at 5 years follow-up, voluntary deltoid, biceps, and triceps activity was achieved. Although only one case has been reported, a new option for the treatment of avulsions may soon be possible.

Other novel avenues in improved treatment for brachial plexus lesions have focused on sensory and cortical re-education, technical improvements in nerve repair, and the elimination of neuromas. Nerve growth factors may provide better results for these difficult injuries. Treatment of avulsions may soon be possible.

ACKNOWLEDGMENTS

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REFERENCES

Restoration of Elbow Flexion after Brachial Plexus Injury: The Role of Nerve and Muscle Transfers

by Karol A. Gutowski, M.D., and Harry H. Orenstein, M.D.

1. ALL OF THE FOLLOWING STATEMENTS ARE TRUE EXCEPT:
   A) Elbow flexion is primarily a function of the C5 and C6 nerve roots
   B) Horner’s syndrome suggests a nerve root avulsion
   C) Lower brachial plexus root (C8-T1) injuries are more common in adult trauma than are upper brachial plexus root injuries (C5-C6-C7)
   D) A nondescending Tinel’s sign suggests the need for surgical exploration of the brachial plexus

2. CURRENT RECOMMENDATIONS FOR DIAGNOSTIC EVALUATION OF NONPENETRATING BRACHIAL PLEXUS INJURIES INCLUDE ALL OF THE FOLLOWING EXCEPT:
   A) Serial examinations of upper extremity motor function
   B) Contrast-enhanced tomography
   C) Magnetic resonance imaging
   D) Electrodiagnostic studies (electromyogram)
   E) Elicitation of Tinel’s sign

3. POTENTIAL DONORS FOR NERVE TRANSFER PROCEDURES TO PROVIDE ELBOW FLEXION IN BRACHIAL PLEXUS INJURIES INCLUDE ALL OF THE FOLLOWING EXCEPT:
   A) Intercostal nerve
   B) Spinal accessory nerve
   C) Musculocutaneous nerve
   D) Contralateral C7 nerve
   E) Partial ulnar nerve

4. COMMON DONORS FOR MUSCLE TRANSFER PROCEDURES TO PROVIDE ELBOW FLEXION IN BRACHIAL PLEXUS INJURIES INCLUDE ALL OF THE FOLLOWING EXCEPT:
   A) Latissimus dorsi
   B) Gracilis as a free tissue transfer
   C) Flexor-pronator mass of the forearm
   D) Sternocleidomastoid
   E) Pectoralis major

5. FACTORS ASSOCIATED WITH POOR OUTCOME AFTER PROCEDURES TO TREAT BRACHIAL PLEXUS INJURIES INCLUDE ALL OF THE FOLLOWING EXCEPT:
   A) Nerve transfer procedures in patients older than 40 years
   B) Transfer of muscles that are grade M3 in strength
   C) Nerve transfer procedures performed more than 12 months after injury
   D) Use of muscle transfers after initial nerve transfer procedures
   E) Avoiding shoulder stabilization procedures

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