Adult traumatic brachial plexus injury

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Introduction

Injury to the brachial plexus in the adult is usually a closed injury and the result of considerable traction to the shoulder. Brachial plexus injury in the adult is an increasingly common clinical problem. Recent advances in neurosurgical techniques have improved the outlook for patients with brachial plexus injuries. The choice of surgical procedure depends on the level of the injury and the radiologist has an important role in guiding the surgeon to the site of injury. This article will describe the anatomy and pathophysiology of traction brachial plexus injury in the adult. The neurosurgical options available will be described with emphasis on the information that the surgeon wants from imaging studies of the brachial plexus. The relative merits of MRI and CT myelography are discussed.

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Anatomy of the brachial plexus

The brachial plexus is formed by the anterior branches of the four lowest cervical spinal nerves, C5–C8, and the first thoracic nerve, T1. The spinal nerves derive from dorsal and ventral roots which arise from the spinal cord. The dorsal roots carry sensory fibres that originate in the dorsal root ganglion that lies within or just beyond the intervertebral foramen. The ventral roots contain fibres with a motor function. Beyond the ganglion is...
the spinal nerve where the dorsal and ventral roots mix together.

The ventral and dorsal roots are not single fibres but are composed of rootlets. These separate rootlets can be defined on MRI with three or four bands in the upper cervical roots (C5–C7) and two bands of rootlets in the lower roots (C8–T1). The length of the rootlets varies from 5–20 mm and join the spinal cord almost one intervertebral disc above their intervertebral foramen. The C5 nerve roots can join the cord as high as C3 so that CT examination should be performed from C3 to T2 to cover the whole brachial plexus.

As the ventral and dorsal roots leave the spinal cord they carry with them an extension of the arachnoid and dura which forms the root sleeve. The root sleeve attaches to the ventral root and spinal ganglion to form the sheath of the spinal nerve so the cerebrospinal fluid (CSF) space does not usually extend beyond the intervertebral foramen. Myelography will therefore only visualize the nerve roots up to the level of the intervertebral foramen and not define the spinal nerves distal to this. The spinal nerves unite to form three trunks, upper (C5 and C6), middle (C7) and lower (C8 and T1; Fig. 1). Each trunk divides into anterior and posterior divisions. Distal to the clavicle the anterior divisions of the upper and middle trunks form the lateral cord and the anterior division of the lower trunk is continued as the medial cord. The posterior divisions form the posterior cord, which lies posterior to the subclavian artery.

The term ‘root injury’ or ‘root avulsion’ refers to avulsion from the spinal cord, rupture in the preganglionic root zone or at the level of the dorsal ganglion in the vertebral foramen. Any injury distal to the ganglion is termed a post-ganglionic injury.

Post-ganglionic supraventricular brachial plexus injury refers to injury of the spinal nerves, trunks and their divisions. Infraclavicular brachial plexus injury refers to injury of the cords and their terminal branches.

Pathophysiology of nerve root avulsion

The great range of motion of the cervical spine produces a unique problem for the cervical spinal nerves. If the spinal nerves had no mobility or elasticity then the roots would be avulsed from the spinal cord by simple rotation of the head. As it is, considerable force is required on the shoulder and upper arm to transmit the force to the roots and lead to avulsion. The nerve sleeve, ganglion and spinal nerve within the foramen are freely mobile allowing the neural structures to adjust, without deformation, to movements of the cervical spine. In the lower cervical spine the spinal nerves are attached to the transverse processes, a protective mechanism not found elsewhere in the vertebral column. With traction on the spinal nerve this attachment to the transverse process may be the first to tear. With greater traction the root sleeve is pulled into the intervertebral foramen and may tear before the root avulses (Fig. 2). A traumatic meningocoele may exist without root avulsion, or at least without avulsion of all the rootlets at a single level, whereas total rootlet avulsion is usually accompanied by a tear of the root sleeve.

Within hours or days, depending on the size of the tear in the root sleeve, cellular proliferation may close the tear leaving a pouch like extension, the meningocoele (Fig. 3). The meningocoele may

Figure 1 Diagrammatic representation of the brachial plexus. LC, lateral cord; PC, posterior cord; MC, medial cord.
not be demonstrated on myelography if cellular proliferation prevents communication between the CSF space and the meningocoele. This is a potential advantage of MRI, which can demonstrate fluid collections that do not communicate with the CSF, as it does not rely on the presence of a contrast agent within the CSF space.

Clinical features and surgical options

A full discussion of the clinical features and surgical options is beyond the scope of this article, and is comprehensively covered elsewhere.\(^8\) The initial management is directed to the associated life-threatening conditions, which include head, spinal and chest injuries. Clavicular and shoulder fractures are associated with infraclavicular brachial plexus injury. With injury of the infraclavicular brachial plexus there is associated subclavian and axillary artery injury in 30% of cases. There are features in the history, and clinical examination that can indicate a pre-ganglionic root avulsion. Horner’s syndrome is characterized by ptosis, meiosis, anhydrosis of the cheek and

Figure 2 (a) Normal anatomical arrangement of the nerve root and nerve root sheath. (b) With increasing traction the fibrous attachment of the nerve root to the transverse process tears. The meninges tear, which can lead to leakage of CSF and meningocoele formation. (c) The elastic strength of the nerve root is exceeded and it tears at its junction with the spinal cord.

Figure 3 (a) Axial T2-weighted MR image showing right traumatic meningocoele, with nerve root avulsion. A tear of the meninges allows CSF to leak into the epidural space and displaces the spinal cord. (b) Coronal T2-weighted MR image of the same patient demonstrates the pouch like meningocoele extending out of the exit foramen (arrows).
enophthalmos. It suggests a pre-ganglionic avulsion of the C8 and T1 nerve roots from which the cervical sympathetic chain arises. Winging of the scapula suggests a pre-ganglionic C6 avulsion, as the serratus anterior is supplied by the long thoracic nerve that arises predominantly from the anterior division of C6, close to the intervertebral foramen. Weakness of the rhomboid muscle suggests C5 root avulsion as it is supplied by the dorsal scapular nerve, which arises from the anterior division of C5, close to its exit from the vertebral foramen. Function of the rhomboid muscle is to move the scapular medially, and is best assessed by asking the patient to bring the elbows together behind the back, with the hands on the hips.

Frequently, however, pre-ganglionic and post-ganglionic injury co-exist so the full extent of the injury may not be realized until surgical exploration. Root avulsion may be complete or incomplete and the roots may be retracted to the supraclavicular region or remain within the exit foramen. In the latter situation there may be a grossly normal appearance on extra-dural surgical exploration and the surgeon must be wary of converting a partial avulsion into a complete avulsion by traction on the nerve in an attempt to assess nerve root integrity. Accurate pre-operative diagnosis of root avulsion is therefore vital. Truly accurate surgical assessment of the intra-dural nerve root can only be achieved by direct examination, but this requires multiple hemi-laminectomies and is not common practice. Chuang’s series of 487 surgically treated closed brachial plexus injuries warrants further discussion, in order to arrive at an understanding of the common patterns of injury. In 75% of cases, root avulsion was present, and in 25% injury was confined to the post-ganglionic plexus. The commonest pattern of root avulsion was total root avulsion of C5 to T1 (43% of root avulsions). The next commonest pattern of root avulsion (29%) was three roots with C5 to C7 being the commonest followed by C7 to T1. Two root avulsion was the next commonest pattern (17%), commonly C5 and C6 or C6 and C7. Four root avulsion occurred in 7%, C6 to T1 and single root avulsion in only 4% with single avulsion of C8 or T1 not described. Multiple root avulsions do not skip a level, always involving adjacent nerve roots. It can be helpful to bear this in mind when determining the integrity of a nerve root, if the nerve root above and below a level are avulsed, then that level is also involved.

The demonstration of a root avulsion does not exclude the possibility of post-ganglionic brachial plexus injury, in fact they often co-exist. The four root avulsion of C6 to T1 is usually associated with a post-ganglionic injury of C5. C7 to T1 three root avulsion is often associated with rupture of the upper trunk. Injury of the infraclavicular brachial plexus alone occurs in 16% of all brachial plexus injuries, supraclavicular injuries alone occur in 5% and spinal nerve injury alone in 4%.

**Surgical options**

Before modern brachial plexus surgery a patient faced the prospect of amputation for a flail and anaesthetic arm. Over the last few decades advances in micro-surgical techniques have improved the prospect for many patients. Results remain better for injuries of the upper brachial plexus as function of the hand is maintained. In these cases restoration of elbow flexion is the goal to allow use of the functioning hand. With injuries of the lower brachial plexus full restoration of hand function is unrealistic but the surgeon will aim to maximize motor function and provide protective sensation to the hand.

The optimal time for surgical reconstruction has been debated over the years with a move towards early intervention. Timing is a balance between the improvements that can occur with conservative treatment and the development of irreversible muscle atrophy that occurs with denervation. Associated injuries often preclude early intervention and surgical repair at three months is a common practice.

The main neurosurgical procedures performed are neurolysis, nerve grafting and neurotization. Neurolysis is the surgical technique of freeing intact nerves from scar tissue. Nerve grafting is the main technique that is used to bridge ruptured nerves. As it requires a length of proximal nerve it cannot be used in pre-ganglionic injuries. The most frequently used donor nerve is the sural nerve, which can yield up to 30 cm of nerve.

The technique of nerve transfer, termed neurotization, is used in pre-ganglionic injuries. This involves the attachment of a donor nerve to the ruptured distal stump, sacrificing the original function of the nerve for a more beneficial result in the upper limb. Commonly an intercostal nerve is used as the donor but a variety of donor nerves have been used including the phrenic nerve, other components of the brachial plexus, so-called plexoplex transfers and even contralateral C7 transfers. The contralateral C7 is used, with an interposed nerve graft, to innervate the median nerve. It is perhaps surprising that sacrificing the function of C7 in the patient’s normal limb leads to little or no neurological deficit.
Until recent years nerve transfer was the only option available for pre-ganglionic injuries. Nerve root repair and re-implantation has recently been described as a new technique. The spinal cord is exposed by performing multiple laminectomies and a graft inserted into a slit in the spinal cord and connected distally to the avulsed roots. In some cases it has proved possible to place the avulsed root directly into the spinal cord. It is too early to say whether this technique will become standard practice, but it has been stated that the clinical benefits reported in the original series are only minor.

**Imaging**

**Myelography and CT myelography**

In 1947 Murphey et al. performed a cervical myelogram for the investigation of a possible disc herniation in a patient who had clinically sustained a traction brachial plexus injury, and made the first demonstration of a traumatic meningocoele. The introduction of water soluble contrast agents enabled better demonstration of the nerve roots and diagnosed a greater number of nerve root avulsions than previously reported. Nagano et al. described a classification system for myelography and compared this with surgical findings in 90 patients. As the surgical exploration only involved extra-dural inspection of the roots rather than the true gold standard of intra-dural examination by multiple laminectomies, the presence of partial avulsions was not diagnosed at surgery. This may explain why slightly abnormal nerve root sheath and obliteration of the tip of the nerve root sheath was not consistently shown to be a sign of nerve root avulsion since it may be a sign of partial avulsion.

The benefits of adding CT to the myelogram was investigated by Marshall and De Silva, comparing both with extra-dural surgical exploration. Myelography achieved a diagnostic accuracy of only 37.5%, although accuracy for the eighth cervical and first thoracic nerve was 75%. Myelography was least accurate at the fifth and sixth cervical nerves, which may be due to the narrow subarachnoid space at these levels. CT myelography was more accurate than myelography at all levels but more so at the C5 and C6 levels, and achieved an overall accuracy of 75%. The authors emphasized that CT may overestimate the intra-dural damage when contrast leaks from an adjacent meningocoele, and that the nerve roots were not consistently visualized, which may be due to the relatively thick (4 mm sections) used. Carvalho et al. achieved an accuracy of 85% using 3 mm sections. This paper is noteworthy because the authors performed multiple hemi-laminectomies to allow direct surgical examination of the intra-dural nerve roots. Partial avulsion of the nerve roots occurred in 19% of root avulsions with 73.3% of partial avulsions occurring at the C5 or C6 level. The commonest pattern of partial avulsion was avulsion of the ventral nerve roots with intact dorsal roots which occurred in 69% of partial avulsions. The occurrence of partial avulsions at the C5 and C6 levels is important as these are the levels where myelography is least accurate. The main advantage that CT adds to a myelogram is the detection of partial avulsions at these levels.

The author’s practice is to perform myelography via a lumbar puncture and run the contrast up into the cervical spine. An early filling film is taken, which can be helpful in cases of marked dural leak when the leakage of contrast obscures the nerve roots from adjacent levels. The myelogram is always combined with a CT examination.

**MRI**

Early interest in the use of MRI in brachial plexus injuries was directed at the post-ganglionic plexus, an area not assessed by conventional imaging. MRI
can detect post-injury fibrosis and neuroma formation in the post-ganglionic plexus. In a small series of cases Hems et al. suggested that in the absence of root avulsions, a completely normal MRI of the supraclavicular plexus excluded significant post-ganglionic nerve disruption. However, when one considers the complexity of the anatomy of the post-ganglionic brachial plexus it is not surprising that MRI cannot identify the precise site of injury, or the severity of damage. Surgery, then, remains the only way of accurately assessing the post-ganglionic plexus. The main focus on the use of MRI has been on the pre-ganglionic plexus with the aim of providing a non invasive means of detecting nerve root avulsion.

Initial studies of MRI using conventional T1 and T2-weighted sequences have shown rather poor accuracy when compared with CT myelography. Carvalho et al. investigated the accuracy of MRI in 60 sets of nerve roots, which were subject to intradural surgical exploration. MRI had an accuracy of only 52% and was technically inadequate for diagnostic analyses in over 30% of cases.

The axial plane has limitations in the ability to delineate the nerve root as the nerve roots pass obliquely, their spinal cord attachment lying one vertebral level above the foramen (Fig. 4). Ochi et al. used axial oblique sections and demonstrated equal accuracy of MRI and myelography. The axial oblique plane is not without difficulties, however, as a greater angle is required going caudally, and the diagnostic accuracy of MRI is greater for the upper roots.

Nakamura et al. used a MRI myelography sequence in a small group of 10 patients and demonstrated a similar degree of accuracy to CT myelography. They used a three-dimensional fast spin-echo volume acquisition, which was heavily T2-weighted. It was subjected to a maximum intensity projection (MIP) algorithm producing a three-dimensional myelogram like image.

Doi et al. used an overlapping coronal oblique MRI sequence and compared this with CT myelography and surgical findings. An axial section through the C4-C5 intervertebral disc was acquired.

Figure 5 (a) Coronal T2-weighted fat-saturation MR image. The obliquely orientated nerve roots are well defined on a coronal sequence. Heavily T2-weighting gives the CSF high contrast and outlines the dural sleeve, giving images similar to a myelogram. (b) A MIP algorithm has been performed. The nerve roots are less clearly defined than on the individual coronal sections, but the MIP gives a good overview. Left C8 and T1 meningocoeles, with nerve root avulsion (arrows).
to determine the direction of the C5 neural foramen. Coronal–oblique cuts parallel to the C–5 neural foramen were then obtained using a turbo spin-echo T2-weighted sequence, 2 mm slices overlapping by 1 mm. Using this technique the accuracy matched that of CT myelography. MRI examined 175 nerve roots and in only five nerve roots were the images unclear. Inter-observer variability was assessed and matched that of CT myelography. The most variable assessment was the diagnosis of partial avulsion (Kappa statistic $\kappa = 0.38$).

One potential drawback of the coronal–oblique technique is that the normal side is not examined and would require additional sequences to be performed. The author’s practice is to perform a myelogram sequence obtained in the coronal plane. A MIP image can be obtained to give an overview but this does not add to the diagnostic information obtained from the source coronal images (Fig. 5).

Spinal cord oedema can be a useful indirect sign of nerve root avulsion (Fig. 6). Axial T2-weighted sequences are performed, and are essential for diagnosing partial nerve root avulsion (Fig. 7). The examination is deemed technically successful if all the nerve roots on the normal side can be seen. The commonest cause of a non-diagnostic image is motion artefact, which is a particular problem when scanning a multiple trauma patient in the early stages, when not only is pain a factor but often poor co-operation due to head injury. A non-diagnostic MRI from other centres can often be successfully repeated when the patient is transferred to our centre, simply because the patient has had a few days to recover from a head injury. A CT myelogram is reserved for those patients in whom a diagnostic MRI can not be performed, and in the author’s practice most patients are now being examined by MRI alone.

**Ultrasound**

Ultrasound imaging of the brachial plexus has been used as a tool to guide brachial plexus anaesthetic blocks. More recently it has been proposed as a...
possible technique for examining the post-ganglionic brachial plexus in cases of injury. It has obvious potential advantages, in terms of high soft-tissue resolution and the ability to follow each component of the plexus as it passes in an oblique plane through the base of the neck. Studies to date have concentrated on the appearances of the non-injured brachial plexus and it remains to be seen whether the technique can reliably identify post-ganglionic brachial plexus injuries, when significant soft-tissue disruption to the normal anatomical landmarks would be expected.

Conclusions

Adult traumatic brachial plexus injury is a potentially severe debilitating injury, commonly affecting individuals in the prime of their life. Recent advances in neurosurgical techniques have improved the outlook for many of these patients. The radiologist plays an important role in guiding the surgeon to the level of the injury and helps plan the surgical approach. Advances in MRI have allowed high-resolution images, which can demonstrate root avulsion, and many patients are now spared the invasive investigation of CT myelography. Motion artefact remains the major drawback of MRI in these patients, who frequently have other injuries.

References