Diagnosis of root avulsions in traumatic brachial plexus injuries: value of computerized tomography myelography and magnetic resonance imaging

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TRAUMATIC brachial plexus injuries are common lesions affecting mainly young individuals. According to major series reported in the literature, motorcycle accidents are the most common cause of traction injuries of the brachial plexus.8,11 Despite the increasing experience with the treatment of brachial plexus lesions over the last decades, the functional outcome remains rather restricted in many of these often young patients, resulting in severely disabling symptoms.

Avulsion of the brachial plexus roots is one of the most important factors that influences the prognosis of these patients. Theoretically, cervical roots may be completely avulsed (both ventral and dorsal) or either ventral or dorsal rootlets alone may be avulsed (Fig. 1). Additionally, rootlets may be in continuity with the spinal cord but still can be ruptured in the intervertebral foramen. Besides that, one of the most important facts is that cervical roots can appear to be intact extradurally in spite of their complete or partial detachment from the spinal cord intradurally.

Several reports have suggested ways to identify whether a lesion is located intradurally (preganglionic) or at the periphery (postganglionic).1,3 Clinical aspects and electromyographic (EMG) findings may be helpful, but unfortunately are not reliable enough to differentiate a pre- from a postganglionic nerve lesion in the majority of cases.

Many reports have been published regarding the value of myelography, computerized tomography (CT) myelography, and recently magnetic resonance imaging (MR) imaging have become the main radiological methods for preoperative diagnosis of cervical root avulsions. Most of the previous studies on the accuracy of CT myelography and MR imaging studies have correlated the radiological findings with the extraspinal surgical findings at brachial plexus surgery. Surgical experience shows that in many cases extraspinal findings diverge from intradural determinations. Consequently, only correlation with the intradural surgical findings will allow assessment of the factual accuracy of CT myelography and MR imaging studies.

In a prospective study, 135 cervical roots (C5–8) were evaluated by CT myelography and/or MR imaging and further explored intradurally via a hemilaminectomy. The accuracy of the preoperative CT myelography–based diagnosis in relation to the intraoperative findings was 85%. On the other hand, MR imaging demonstrated an accuracy of only 52%. The most common reasons for false-positive or false-negative findings were: 1) partial rootlet avulsion; 2) intradural fibrosis; and 3) dural cystic lesions. Computerized tomography myelography scans using 1- to 3-mm axial slices prove to be the most reliable method to evaluate preoperatively the presence of complete or partial root avulsion in traumatic brachial plexus injuries.

Because extradural judgment of cervical root avulsion can be unreliable, accurate assessment of intraspinal root avulsion enormously simplifies the decision concerning the choice of donor nerves for transplantation and/or neurotization during brachial plexus surgery.

KEY WORDS • brachial plexus • root avulsion • computerized tomography • magnetic resonance imaging • computerized tomography myelography
reliable if compared to the intradural status of the nerve roots.

Surgical Anatomy

Knowledge of the microsurgical anatomy of the cervical spine is fundamental to the evaluation of the status of the cervical roots (C5–8) after brachial plexus injuries. Localization of the anterior root exit zone and posterior root entry zone at the different cervical levels is essential. Anterior cervical roots are formed by a group of rootlets that exit from the spinal cord 1 to 3 mm away from the midline. Their diameters range from 1.5 to 3 mm. Longitudinal length from the spinal cord to the intervertebral foramen varies from 5 to 20 mm.9 The dorsal roots are usually thicker than the ventral roots and have a slightly shorter longitudinal length.

Concerning the level of the anterior root exit zone and the posterior root entry zone, microsurgical dissection has shown that ventral and dorsal roots join the spinal cord almost one intervertebral disc above their intervertebral foramen. It means, for example, that the C-5 root joins the spinal cord at the level of the intervertebral disc C3–4 or just below it.

Clinical Material and Methods

Patient Population

During a 6-month period in 1993 and 1994, 40 patients were admitted to our department for treatment of posttraumatic lesions of the brachial plexus. Clinical and electrophysiological studies obtained in these patients did not completely exclude the possibility of cervical root avulsion in one or more levels of the brachial plexus. Therefore, a prospective study was conducted to define the intraspinal integrity of the affected cervical roots and also the accuracy of CT myelography and magnetic resonance (MR) imaging in the diagnosis of root avulsions after traction injuries of the brachial plexus. All of the patients were included in this prospective study.

Of these 40 patients, there were 38 males and two females. The average age at the time of admission was 27 years (range 17–59 years). In 28 patients, clinical and EMG assessment showed a complete lesion of the upper and lower brachial plexus. In 12 cases, despite the clinical diagnosis of brachial plexus palsy, EMG studies revealed signs of reinnervation in some muscles. Motorcycle accidents were the cause of injury in 95% of the patients. The interval between the accident and the hospital admission for treatment of posttraumatic symptoms ranged from 3 to 15 months, with an average of 7.2 months.

Neuroradiological Assessment

A CT myelography and/or MR imaging study was obtained preoperatively in all patients to diagnose root avulsion of the brachial plexus. Computerized tomography myelography was performed 90 to 120 minutes after intrathecal injection of 15 to 20 ml of contrast medium into the lumbar spin.

Computerized tomography was obtained from C4–T1 with 3-mm axial slices. In cases of pathological or doubtful findings, 1-mm axial slices were acquired in addition. The scan angle was parallel to the cervical discs. A total of 75 cervical roots was preoperatively evaluated with CT myelography scans.

Magnetic resonance imaging was performed using a 1.5-tesla unit. All images were obtained using a spinal cord coil. A 128 × 256 matrix and a 120-mm field of view were used. The T1- (repetition time 21 seconds, echo time 6.8 seconds) and T2-weighted sequences (repetition time 5380 msec, echo time 300 msec) were both obtained in the coronal and axial planes. Axial slices were 3 mm thick. Flash sequences and artifact suppression techniques were also used. The intradural integrity of 60 cervical roots was evaluated preoperatively using MR imaging studies.
Both CT myelography and MR images were evaluated preoperatively by at least two different observers to analyze the status of the cervical rootlets from C5–8. The CT myelography scans and MR images in which the observers were not able to identify the ventral and dorsal rootlets of the intact side were excluded and classified as uninterpretable scans due to technical pitfalls. Image criteria for the diagnosis of root avulsion was based on the absence of either one (partial avulsion) or both rootlets (complete avulsion) but was not based on the presence of a meningocele. When both ventral and dorsal roots were visualized from the spinal cord to the intervertebral foramen on axial slices, an intact root was suspected. Analysis of each avulsed or intact root on CT myelography and MR imaging axial slices was compared with the contralateral intact side.

**Surgical Technique**

Intradural surgical exploration of the cervical roots was performed via a hemilaminectomy at C-5 and/or C-7 (Fig. 2). A partial hemilaminectomy of C-4 was performed additionally to expose the C-5 root where it joins the spinal cord. Thereby, with the aid of the microscope, the surgeon was able to inspect both ventral and dorsal rootlets from C5–8. If only the upper cervical roots (C-5 and C-6) needed exploration, as in isolated upper brachial plexus palsy, the C-7 lamina was left intact. Each rootlet (ventral and dorsal) was evaluated from the spinal cord as far as the intervertebral foramen, because roots may be ruptured in different sites even intradurally.

**Intraoperative Monitoring**

Each patient was monitored intraoperatively using somatosensory evoked potentials. Additionally, stimulation of the intact dorsal roots was performed intradurally and the somatosensory evoked potential was recorded from the sensory cortex by subdermal needle electrodes implanted in the scalp. Stimulation usually ranged from 0.5 to 3 mA.

**Results**

**Computerized Tomography Myelography**

Twenty-five patients underwent preoperative CT myelography to diagnose the extent of the intradural root damage. Furthermore, each patient underwent a hemilaminectomy to verify the integrity of the cervical roots and correlate them with the radiological findings.

The CT myelography findings demonstrated the presence of intact roots, ventral or dorsal avulsed rootlets, or complete root avulsions (Fig. 3). Intact roots were found...
in 46% of the cases, complete root avulsions in 43%, and partial root avulsion in only 11%.

Eighty-five percent of the roots evaluated by CT myelography and correlated to the intradural surgical findings showed a perfect correlation. In the other 15% there was disparity between the surgical findings and the preoperative radiological evaluation. The accuracy of the CT myelography was then evaluated regarding the different cervical roots (C4–8) (Fig. 4). Interestingly, roots that were incorrectly diagnosed from radiological studies were exclusively C-5 or C-6 roots. In only one case were CT myelography studies excluded due to technical problems.

Magnetic Resonance Imaging

Among the 135 roots that were inspected intradurally to determine the extent of the preganglionic lesion, 60 (in 15 patients) were submitted preoperatively to MR imaging. Magnetic resonance imaging demonstrated 10 intact roots, 23 completely avulsed roots, and four partially avulsed roots (Fig. 5). The magnetic resonance images were technically inadequate for diagnostic analyses in 23 cervical roots.

In this series, MR imaging provided an accurate diagnosis in only 52% of the cases. In 48%, MR images showed unreliable or inconsistent findings when correlated with surgical findings on hemilaminectomy (Fig. 6).

Surgical Findings

A total of 135 roots was inspected intradurally. In 64 cases complete root avulsion was observed. Intact roots (ventral and dorsal) were found in 56 cases. Partial avulsion of the ventral or dorsal rootlet was discovered in just 15 cases (Fig. 7). Complete root avulsion was found more
frequently in C-7 and C-8 roots. Among the 64 cases of complete root avulsion, 43 cases (67%) were at C-7 or C-8 cervical roots. In contrast, 44 roots (78.5%) of the 56 cases of intact cervical roots were C-5 or C-6.

Combinations of intact ventral rootlet and avulsed dorsal rootlet or vice versa were also observed. In 11 of these cases (73.3%) the ventral rootlet was avulsed and the dorsal rootlet was preserved (Fig. 7B). In one case in our series, avulsion of the ventral root was present at the level of the intervertebral foramen (Fig. 8). Furthermore, 73.3% of all the partial root avulsions occurred at C-5 or C-6 nerve roots.

Correlation Between Neuroradiological and Surgical Findings

To define further the distribution of misdiagnosis for both neuroradiological procedures, a detailed comparison was made on each root level. Figure 9 (upper) shows that in the majority of cases of complete root avulsion (ventral and dorsal) or intact roots, CT myelography and hemilaminectomy displayed a good correlation. Interestingly, there were two cases of false-positive radiological findings in which CT myelography revealed only an intact ventral rootlet and in one case intact ventral and dorsal roots. However, surgical exploration (hemilaminectomy) demonstrated complete root avulsion in both cases. In contrast, two cases of intact dorsal rootlets or intact ventral and dorsal roots were missed by the CT myelography. In one case, just the ventral but not the dorsal rootlet could be identified correctly by CT myelography.

Similarly, diagnosis of root avulsion on MR images that were technically satisfactory was correct in 31 of 37 cases (Fig. 9 lower). In two cases a dorsal rootlet was missed on the MR images and in four other cases MR imaging did not show the ventral rootlet. This comparison highlights the good correlation between both neuroradiological methods, although a higher number of MR images had to be omitted from this analysis due to technical pitfalls, as already mentioned.

These results also stress the fact that there are individual cases in which the neuroradiological diagnosis may be partially or completely misleading. Regarding the presence of posttraumatic meningoceles, especially on CT myelography scans, correlation of the hemilaminectomy findings and the radiological findings demonstrated cases of meningocele with partial root avulsion and with intact roots. On the other hand, complete root avulsion was not frequently associated with posttraumatic meningocele on CT myelography studies.

Discussion

Accurate assessment of the site and extent of the injury is imperative in patients with traction injuries of the brachial plexus. Therefore, the determination of whether the lesion spot is pre- or postganglionic in location will directly affect the patient’s prognosis and the surgical strategy. Regarding the preoperative diagnosis of cervical root avulsion, clinical and especially electrophysiological studies are helpful, but unfortunately not reliable enough in a great number of cases.
The standard myelogram has been used extensively over many years to evaluate root avulsions after severe traumatic injuries of the brachial plexus. Traumatic meningocele was considered a proof of root avulsion. However, subsequent reports have shown that traumatic meningocele does not necessarily signify root avulsion. On the other hand, a normal myelographic finding does not assure the integrity of the intradural rootlets. Although some authors have tried to show the different alterations found in the myelogram, large series demonstrated an accuracy of between 60% and 70% and emphasized the importance of false-positive or false-negative findings. It should be stressed that these results were correlated with the surgical findings on extradural exploration of the brachial plexus. Likewise, cases in which the root was intact extraforaminally but damaged intradurally were considered normal surgical findings and wrongly associated with the myelographic finding. Thus, it may be assumed that the real accuracy of the standard myelogram is even lower than reported. Furthermore, partial rootlet avulsions (ventral or dorsal) cannot be diagnosed by myelography.

Computerized Tomography Myelography

Due to technical improvements and increasing experience, CT myelography provided a reliable correlation and diagnosis of the extent of intradural damage after traction injuries of the brachial plexus in 85% of our cases. To visualize all the brachial plexus roots (C4–8 roots), axial slices should begin immediately at the upper border of C-4 and extend down to the lower border of the first thoracic vertebral body. In good quality CT myelography scans with 3-mm axial slices, ventral and dorsal rootlets can be visualized on both sides in cases of intact intradural roots.

Traumatic meningocele and intradural fibrosis are usually the factors responsible for preoperative misdiagnosis in interpreting the CT myelography scans. Likewise, traumatic cystic lesions resulting from a dural leak should also be carefully evaluated with 1-mm axial slices. Intradural surgical exposure in such cases may display partial root avulsions or even intact roots in some cases.

Intradural fibrosis, especially in cases of partial rootlet avulsion at the upper levels (C-5 and C-6) is also commonly responsible for either false-positive or false-negative preoperative radiological diagnosis. Even using the 1-mm axial slice technique, only surgical exploration will clarify the status of the cervical roots in some patients. Interestingly, most of the cases of preoperative misdiagnosis were at the C-5 and C-6 levels. Narrow subarachnoid space at the upper levels of the spinal cord due to the cervical intumescentia, and the fact that most of the partial rootlet avulsions are located at these levels, may play an important role.

Magnetic Resonance Imaging

Magnetic resonance imaging offers a good visualization of the brachial plexus beyond the spinal foramen. Several reports have proven the usefulness of this method in the diagnosis of distal lesions. High-field strength MR imaging with multiplanar views can well distinguish the nerves at the periphery from the surrounding vessels and muscles. On the other hand, delineation of the intradural rootlets (ventral and dorsal) may be difficult in the majority of patients with traction injuries of the brachial plexus. Commonly, these patients suffer from severe deafferentation pain and are not able to lie as still as is required during the MR procedure. Consequently, most of the doubtful and technically inadequate MR images are due to motion artifacts. Additionally, axial slices are usually 3 to 5 mm thick, providing a poor correlation with intradural rootlets, which measure 1.5 to 3 mm.
Diagnosis of root avulsions in brachial plexus injuries

In our experience, correlation of the intradural surgical findings with MR imaging studies is not reliable in the preoperative diagnosis of root avulsions in approximately 48% of patients. Most often in our series this was due to partial root avulsions, intradural fibrosis, and traumatic meningocele as well as technical pitfalls.

Implications for Future Management

Accurate assessment of the site (pre- or postganglionic) and extent of the individual cervical nerve root injury is imperative and will directly affect the surgical strategy and prognosis in patients with traction injuries of the brachial plexus.20,25

One of the major issues and generally the first step during the surgical treatment of brachial plexus lesions is the decision about the intactness of the cervical roots C5–8.11,14 Depending on cervical root integrity, nerve transplantation with grafts and/or nerve transfers should be performed to repair important structures of the brachial plexus. Because of the severe fibrosis that is usually found in such cases, the proximal exposure of the cervical roots up to the neuroforamen can be very time consuming and bears certain risks. Intraoperative nerve action potentials obtained at the proximal cervical root (just past the neuroforamen) attempt to evaluate the intraspinal status of the roots extraspinally.4 However, nerve action potential studies assess only the dorsal rootlet. Thus even an intact root Exiting from the intervertebral foramen does not assure its intraspinal integrity.

Our experience with brachial plexus surgery has revealed many cases in which intraspinal findings displayed complete or partial root avulsion despite extradural root integrity. Consequently, some cases of unsuccessful nerve grafting can be the result of previously unidentified isolated intraspinal complete or partial root avulsion. In our opinion, hemilaminectomy and inspection of the cervical roots in cases of inconclusive preoperative radiological studies will provide the following advantages for further surgical management: 1) nerve grafting on questionably intact extradural roots that are actually intradurally damaged is avoided; 2) accurate preoperative diagnosis of available cervical roots for transplantation is obtained; 3) exact preoperative planning with the patient regarding the necessity of nerve transfer is possible; and 4) in cases of documented root avulsion, direct exposure and performance of extraplexal nerve transfers is possible without further peripheral surgical exploration of the cervical roots.

Conclusions

Accurate assessment of the extent of intradural nerve root damage after traumatic brachial plexus injuries is essential for planning the surgical repair strategy. In 85% of patients, CT myelography with 1- to 3-mm axial slices provides a reliable preoperative diagnosis concerning the presence of intact root and complete or partial root avulsions. Magnetic resonance imaging using standard techniques only allows an accurate diagnosis of root avulsion in 52% of cases. Motion artifacts are one of the major causes of inadequate MR images, making the preoperative neuroradiological interpretation of these studies very difficult. Improvement of respiratory compensation systems, new artifact suppression techniques, and the use of special coils to improve the signal-to-noise ratio in high-field MR imaging, will certainly provide us with a more accurate image assessment of the intradural rootlets in brachial plexus injuries in the future. Therefore, the preoperative radiological assessment should include a CT myelography study and, in the approximately 15% of patients in whom CT myelography does not display the nerve roots, a hemilaminectomy should be performed to clarify the status of the affected cervical nerve roots of the brachial plexus. Concerning the further surgical treatment of these patients, accurate preoperative diagnosis of complete or partial root avulsion is of definite benefit. Nerve grafting in questionably intact roots as determined on extradural studies is avoided and support is given for the intraoperative selection of potentially useful donor nerves for transplantation and/or neurotization of the brachial plexus.

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References


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