Cervical nerve root avulsion in brachial plexus injuries: magnetic resonance imaging classification and comparison with myelography and computerized tomography myelography

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Object. The authors describe a new magnetic resonance (MR) imaging technique to demonstrate the status of the cervical nerve roots involved in brachial plexus injury. They discuss the accuracy and reproducibility of a MR imaging–derived classification for diagnosis of nerve root avulsion compared with those of myelography combined with computerized tomography (CT) myelography.

Methods. The overlapping coronal–oblique slice MR imaging procedure was performed in 35 patients with traumatic brachial plexus injury and 10 healthy individuals. The results were retrospectively evaluated and classified into four major categories (normal rootlet, rootlet injuries, avulsion, and meningocele) after confirming the diagnosis by surgical exploration with or without spinal evoked potential (EP) measurements and by referring to myelography and CT myelography findings. The reliability and reproducibility of the MR imaging–based classification was prospectively assessed by eight independent observers, and its diagnostic accuracy was compared with that of traditional myelography/CT myelography classification, correlated with surgical and spinal EP findings in another 50 cervical roots in 10 patients with traumatic brachial plexus injury.

Conclusions. In the retrospective study in which MR imaging and myelography/CT myelography findings involving 175 cervical roots in 35 patients were compared, the sensitivity of detection of the cervical nerve root avulsion was the same (92.9%) with both modalities. In the prospective study, interobserver reliability and intraobserver reproducibility showed that there was no statistically significant difference between MR imaging and myelography/CT myelography and that their accuracy for detecting cervical root avulsion was the same as that in the retrospective study. The overlapping coronal–oblique slice MR imaging technique is a reliable and reproducible method for detecting nerve root avulsion. The information provided by this modality enabled the authors to assess the roots of the brachial plexus and provided valuable data for helping to decide whether to proceed with exploration, nerve repair, primary reconstruction, or other imaging modalities.

KEY WORDS • magnetic resonance imaging • computerized tomography myelography • myelography • brachial plexus avulsion

Traction-induced lesions of the brachial plexus can be situated within the spinal canal or more distally at the level of the trunk or cord. Surgical management and prognosis of these injuries depend on the accurate diagnosis of the nerve root avulsion. Recently, advances in microsurgical techniques have allowed surgeons to achieve successful nerve repair not only in the case of distal lesions but also in the more proximal nerve root injuries.12 This has necessitated the determination of detailed pathological features of the nerve roots by performing clinical, electrophysiological, and radiological examinations.13 The authors of several reports have suggested various ways to distinguish whether the location of a lesion is intradural (preganglionic) or peripheral (postganglionic).10,13,14 Clinical and electromyographic findings may be helpful, but they do not allow for reliable differentiation of a pre- and postganglionic nerve lesion in the majority of cases.13 Preoperative neuroimaging of brachial plexus injury has previously been performed using myelography10,14 and postmyelography CT scanning.15,17 Both modalities, however, involve considerable risk of exposure to radiation, possible adverse reaction to contrast material, and the risks associated with lumbar puncture. Although they provide information for proximal lesions within the subarachnoid space, none is provided for the lesions distal to the intervertebral foramen where the roots of the plexus can be repaired.

In 1987, Blair, et al.,1 described the MR imaging appearance of the normal brachial plexus in the cervicoaxil-
lary region. Although several studies of MR imaging techniques for assessing brachial plexus injury were subsequently reported, these methods did not demonstrate results superior to conventional imaging modalities such as myelography and CT myelography.† To overcome these problems and improve contrast to provide better-quality images of the nerve roots, we developed a new technique of MR imaging in which overlapping slices are obtained. We describe the method by which overlapping coronal–oblique MR imaging slices are obtained and how this modality is used to demonstrate the lesions of involved nerve roots in patients in whom clinical and EMG diagnoses of brachial plexus injury have been established. We compare the accuracy of our imaging technique with that of conventional myelography/CT myelography and examination of the roots during surgical exploration, with or without measurement of intraoperative spinal EPs. We also assessed the interobserver reliability and intraobserver reproducibility to evaluate the accuracy and reproducibility of this new technique compared with those of myelography and CT myelography.

Clinical Material and Methods

The project consists of two studies. In the first we performed preliminary classification of cervical nerve root lesions based on MR imaging and compared it for accuracy and diagnosis of root avulsion with conventional myelography combined with CT myelography before undertaking surgical exploration of the involved root and measurement of spinal EPs. In the second study we assessed the interobserver reliability and intraobserver reproducibility to evaluate the MR imaging–based classification.

We obtained informed consent from each patient and the study protocol was reviewed and approved by the institutional review committee of our institute.

Study 1: MR Imaging Classification

Patient Population. Between January 1995 and December 1997, 35 patients with traumatic brachial plexus injury underwent MR imaging, myelography, and CT myelography prior to surgical exploration and secondary nerve reconstruction. Patient demographic data and results of each classification in Studies 1 and 2 are listed in Table 1. The images obtained in these 35 patients were retrospectively evaluated for the accuracy of their MR imaging–based classification of cervical root avulsion, compared with that provided by conventional myelography, CT myelography, and intraoperative pathological findings. Magnetic resonance images of the cervical roots acquired in 10 healthy individuals were also evaluated to determine the variations within the normal range.

Magnetic Resonance Imaging: Preparation. The patient was positioned supine with arms by the side. A small pillow was placed beneath the head to flex the cervical spine and align its lordotic curve in a straight line. The patient was asked to avoid deep breathing and swallowing throughout the procedure to minimize any motion artifact. A surface coil for the cervical spine (CP Neck Array; Siemens, Erlangen, Germany) was applied to optimize the FOV for imaging of the proximal portion of the brachial plexus. This also provided a uniform signal-to-noise ratio across the imaging field, which was necessary for the overlapping slice technique. No intravenous contrast agent was administered.

Magnetic Resonance Imaging: Equipment and Technique. Magnetic resonance images were obtained using a 1-tesla Magnetom unit (Siemens). First, the transverse (axial) sequence through the C4–5 intervertebral disc was acquired to determine the direction of the C-5 neural foramen. Coronal–oblique cuts parallel to the C-5 neural foramen were then obtained using turbo spin–echo T2-weighted imaging techniques. Five coronal–oblique slices were obtained by transpositioning the cursor 1 mm each time, from the anterior tubercle of the transverse process of C-5 to its posterior tubercle (Fig. 1). The slice thickness was set at 2 mm, and each slice overlapped the adjacent slice by 1 mm (TR 4000 msec, TE 130 msec, number of acquisitions six to eight times, FOV 250 mm, 120 × 256 matrix, rectangular FOV 6/8). Fat suppression was not used. Images of all five roots were included either in one or two adjacent coronal–oblique slices. After obtaining a separate image of each of the five roots, they were reconstructed to maximum intensity projection to obtain a high-contrast image of the rootlets and roots. Coronal–oblique acquisition times were 5 minutes for single and 25 minutes for five acquisitions.

Classification of MR Imaging Findings. Imaging findings were retrospectively classified after confirmation of the pathological region of each cervical root in 35 patients by

<table>
<thead>
<tr>
<th>Type of Paralysis (roots involved)</th>
<th>Study 1 (retrospective)</th>
<th>Study 2 (prospective)*</th>
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<tbody>
<tr>
<td>C5–T1 16</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>C5–6 8</td>
<td>1</td>
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<tr>
<td>C5–7 7</td>
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<tr>
<td>C5–8 3</td>
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<tr>
<td>C7–T1 1</td>
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<tr>
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<td>Zone 3–4 26</td>
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<tr>
<td>normal 42</td>
<td>11</td>
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<tr>
<td>meningocoele (M) 50</td>
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<tr>
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<td>avulsion (A) 39</td>
<td>80, 77</td>
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<tr>
<td>normal (N) 75</td>
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<tr>
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<td>avulsion (A) 40</td>
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<tr>
<td>normal (N) 77</td>
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<td>total 175</td>
<td>400, 400</td>
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* The two values listed in the classification columns represent those obtained during the first and second evaluations.
† See Fig. 6 for exact definitions of lesions.

TABLE 1

Results of cervical root classification based on imaging and intraoperative findings in Studies 1 and 2
Comparison with findings at surgical exploration, intraoperative electrophysiological study, as well as referring to conventional myelography and CT myelography classification.

In good-quality MR images, the sensory rootlets, motor roots, and dorsal ganglion were clearly demonstrated in a single coronal-oblique section. The rootlets and ganglion, however, were also sometimes seen separately in the adjacent two or three slices. Magnetic resonance images of the cervical roots obtained in 10 healthy individuals were also evaluated to determine variations that were within the normal range. Generally, the rootlets of the upper roots (C5–7) were well visualized as three or four bands with a round-looking ganglion whereas the rootlets of the lower roots (C8–T1) appeared as two bands with a flat-looking ganglion (Fig. 2). Magnetic resonance images were classified by assessing the rootlets within the intradural space and the dorsal ganglion root within the intervertebral foramen (Fig. 3). When the coronal-oblique sections revealed three or four intact rootlets within the intradural space of C5–7 and one or two intact rootlets in C8–T1, this was considered to be a normal (N) rootlet (Fig. 2). The normal rootlet should have a normal root and ganglion within the intraforaminal space. In cases in which there were fewer than the normal number of rootlets with visible distortion, and the absence or displacement of the ganglion in the intraforaminal space, the lesion was classified as a partial avulsion (R). The absence of rootlets without a meningocele was designated as an avulsion (A) (Fig. 4). In some cases a meningocele (M) was present (Fig. 5). In some instances, artifact shadows of low T2-weighted signals were noted in the ganglion, and these images were excluded from the study. The MR imaging findings in each root demonstrated on all images obtained in every patient were correlated because the images of individual rootlets were sometimes obtained in different slices.

Control Myelography. Myelography was performed preoperatively using a 240-mg/dl concentration of Iotrolan (Isovist) after making a lateral puncture between the C1–2 vertebrae. It was our experience that details of root and rootlet lesions were better visualized on myelograms obtained after lateral C1–2 interval puncture than after lumbar puncture. Based on modification of the myelographic classification proposed by Nagano, et al., the myelographic findings were classified into six categories (Fig. 6).

Control CT Myelography. After myelography, 3-mm axial slice CT myelograms were obtained from C-4 to T-1. When in doubt or when evident disease was detected on the initial scan, additional 1-mm axial slices were obtained. The angle at which we obtained the scan was oriented parallel to the cervical discs. A CT myelographic diagnosis of root avulsion was based on the absence of either one (P) or both ventral and dorsal roots (A) or the presence of a meningocele (M). When axial scans revealed both ventral and dorsal roots from the spinal cord.
to the intervertebral foramen, the root was considered to be intact (N) (Fig. 7). Determining the presence of an avulsed or intact root was further aided by comparison with the contralateral intact root. When the root of the intact side could not be identified, the affected root was classified using only myelography.

Although the exact pathological anatomy of each category is different, partial lesions, complete lesions, and meningoceles in all imaging classifications (myelography, CT myelography, MR imaging) were all considered to be avulsions.

Surgical Exploration and Intraoperative Spinal EP Monitoring. Each patient underwent surgical exploration of the brachial plexus and intraoperative nerve root spinal EP monitoring. The involved roots were identified and electrically stimulated after exposure of the brachial plexus. The EP was recorded from the preoperatively placed epidural electrode to assess the continuity of the root with the spinal cord. Finally, the level of brachial plexus injury was diagnosed and classified according to the modified classification of Nagano, et al.10 (Fig. 8). The involved roots were classified as avulsion in Zones I to II-A, when no spinal EP could be recorded and no roots were present in the intraforaminal space. Zones II-B to IV could be classified only when spinal EP could be recorded from the intact nerve root. Both MR imaging– and CT myelography–derived classifications for all 175 roots were compared with respect to their ability to detect root avulsion based on the zone classification (Fig. 8) noted during surgical exploration, with or without the measurement of spinal EP.

Study 2: Assessment of Reliability, Reproducibility, and Accuracy of Classification

After preliminary MR imaging classification, another 50 cervical roots in 10 patients with brachial plexus injury were studied to assess the reliability, reproducibility, and accuracy of the MR imaging classification.

Eight independent observers blinded to the patients’ identities and clinical presentations of the MR imaging classification evaluated the results, using myelography/CT myelography and MR imaging prospectively, and all the roots were classified into the appropriate, previously described individual categories. This was conducted for assessment of interobserver reliability to determine the number of observers who agreed to the same diagnosis. All observers were given the same images 6 weeks later and asked to repeat the classification, access to their earlier interpretation being denied. This was done to assess the intraobserver reproducibility to verify consistency of diagnosis of the same condition by the same observer. All eval-

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**Fig. 3.** Classification of MR imaging findings of the rootlets in the intradural space: N = normal; R = partial injury to the rootlets; A = complete avulsion of rootlets without meningocele; M = meningocele.
Elevation sessions were conducted prior to surgery. For evaluation of accuracy in assessing the root avulsion, all the first and second evaluations were summarized and compared between MR images and myelography/CT myelograms. When the observers were unable to identify the ventral and dorsal rootlets of the intact side on the CT myelograms, the involved roots were classified only by myelography. Thereafter, surgical exploration of the involved brachial plexus and intraoperative measurement of spinal EPs were performed to confirm the level and nature of the lesions.

Statistical Analysis

We used the McNemar chi-square test to compare the sensitivity and specificity of the different modalities and the Cohen Kappa analysis for interobserver reliability and intraobserver reproducibility of each classification. Statistical analysis for significance was performed using the Student t-test for paired and unpaired continuous variables. The level of significance was established at $p < 0.05$.

Results

Study 1: Preliminary MR Imaging Classification

Retrospectively, 170 (97%) of 175 nerve roots could be classified by MR imaging. Findings were classified as normal in 77, partial avulsion in 40, avulsion in nine, and meningocele in 44 (Table 1). Five roots could not be classified because the MR images were unclear and were included as the negative data for statistical analysis.

On the other hand, all 175 roots could be classified using myelography, and 26 (14.8%) of 175 roots could not be evaluated by CT myelography because of poor-quality images. The much lower rate of CT myelography detection led us to assess cervical roots by using both myelography and CT myelography. Combined myelography/CT myelography findings were classified as meningocele in 50 roots, partial avulsion in 11, avulsion in 39, and normal in 75.

The sensitivity and specificity of our MR imaging technique for detecting the presence of root avulsion were 92.9% and 81.3%, respectively ($p = 0.037$). Similarly, in myelography and CT myelography, 84 avulsed roots were classified as M in 47, D in 10, A in 21, and N in six cases.
The sensitivity and specificity of myelography/CT myelography were 92.9% and 75.8%, respectively ($p = 0.005$).

Results of both MR imaging and myelography/CT myelography classifications for all 175 roots were compared with respect to their ability to detect root avulsion based on the zone classification (Fig. 8) noted on surgical exploration with or without the measurement of spinal EP. There was no statistically significant difference in the successful imaging rates for diagnosing root avulsion between these two imaging modalities.

Study 2: Reliability and Reproducibility

The $\kappa$ coefficients for the interobserver reliability of the first and second MR imaging evaluations were 0.49 and 0.70, respectively, and those of myelography/CT myelography were 0.67 and 0.69, respectively. The agreement indicated by the coefficient in the second MR imaging evaluation improved markedly, but that achieved in myelographic evaluation remained nearly the same as the first. The $\kappa$ coefficient for interobserver reliability for the second evaluation was essentially the same (0.69) for both the categories. There was no statistical difference between the two, and these values can be interpreted as substantial.
by the Landis and Koch method. Among four categories of each classification, the highest \( \kappa \) coefficient was found in MR imaging–detected cases of meningocele (M) (\( \kappa = 0.90 \)) and in myelography–documented cases of normal (N) roots (\( \kappa = 0.81 \)). In contrast, the lowest \( \kappa \) coefficient was found in MR imaging–detected cases of partial avulsion (R) (\( \kappa = 0.38 \)), as well as in myelography–documented cases of partial avulsion (D) (\( \kappa = 0.26 \)). The \( \kappa \) value of the intraobserver reproducibility (for all eight observers) was 0.58 ± 0.07 (range 0.28–0.96) when studying MR images and 0.78 ± 0.02 (range 0.53–0.96) when assessing myelograms. There was no statistical difference between modalities (\( p = 0.1168 \), unpaired t-test). The accuracy for detection of root avulsion by all observers was compared using the McNemar chi-square test. The MR imaging detection–related sensitivity and specificity of the avulsion at the second evaluation were 88.84% and 71.59%, respectively (\( p = 0.006 \)), and those for myelography were 91.96% and 71.59%, respectively (\( p = 0.0002 \)). Both modalities had statistically different accuracy for detection of cervical root avulsion (\( p < 0.05 \)).

**Discussion**

The overlapping coronal–oblique slices MR imaging technique described here provided clear images of the rootlets, roots, and ganglia in one to three adjacent sections. By overlapping each 2-mm slice by 1 mm with the adjacent slice, the chances of missing these structures are minimized. With this two-dimensional overlapping technique, unclear images of rootlets, roots, or ganglia in one slice may be enhanced by reconstructing the adjacent three or four slices to the maximum intensity projection to obtain higher-contrast images of these structures without increasing the artifacts of noise.

Differentiating root avulsion from the distal rupture is the most important factor for deciding the mode of treatment in the brachial plexus injury. Myelography and CT myelography are invasive techniques but are conventionally used to assess patients. The overlapping coronal–oblique slice MR imaging technique was helpful in evaluating 170 (97%) of 175 roots in the retrospective study, classified into four categories for detection of root avulsion. Sensitivity and specificity for MR imaging–based detection of root avulsion were the same as those when conventional myelography/CT myelography was used. In the prospective study, there was no \( \kappa \) value–based difference in interobserver reliability between each modality at the second evaluation. It was nearly the same, however (0.67 and 0.69, first and second evaluations, respectively) for myelography/CT myelography in both the evaluations. It was lower for MR imaging in the first study (0.49 compared with 0.7). Similarly, the highest \( \kappa \) value for intraobserver reproducibility was the same (0.96) for both groups. The lowest values for MR imaging and myelography/CT myelography were 0.28 and 0.53, respectively. The low \( \kappa \) values for interobserver reliability in the first evaluation and intraobserver reproducibility for MR imaging were due to the fact that some observers were not familiar with evaluating the present overlapping coronal–oblique slice images. The higher value for interobserver reliability demonstrated at the second evaluation indicates that the accuracy of MR imaging assessment can be improved further by practice. The values for myelography/CT myelography did not vary much because all observers were accustomed to evaluating these conventional images.

In our MR imaging classification, partially avulsed lesions received the most variable assessments by the observers (\( \kappa = 0.38 \)), being frequently diagnosed as normal compared with those that were more easily classified into the avulsion and meningocele categories. Conventional myelography and CT myelography may be necessary to supply further information only when the roots were classified as partially avulsed on MR imaging.

The overlapping coronal–oblique slice MR imaging technique has many advantages. It is noninvasive and there are no risks related to exposure to radiation, lumbar puncture, and adverse reaction to contrast agents. In addition, postganglionic lesions of distal peripheral structures of brachial plexus such as trunks and cords can also be evaluated. The status of these structures cannot be determined using myelography. Myelography after lateral cervical puncture provides superior imaging quality, although it is a technically difficult procedure. In the retrospective study all 175 roots could be classified because of superior image quality, which may not be true for myelography after lumbar puncture, and we believe that overlapping coronal–oblique slice MR imaging may be superior in this situation. Furthermore, it does not require additional technical skill. Other MR imaging techniques failed to allow us to diagnose rootlet injuries, which can otherwise be identified using our technique.

**Conclusions**

The overlapping coronal–oblique slice MR imaging...
technique is a reliable and reproducible method for detecting nerve root avulsions. On the basis of the findings in our present study, we have modified our treatment of patients with brachial plexus injury. Patients in whom an MR imaging–documented diagnosis of avulsion or meningoccele is established using our new technique undergo a primary reconstructive procedure rather than surgical exploration of the brachial plexus. If a partially avulsed lesion was suspected on MR imaging, myelography combined with CT myelography was performed to document the avulsion, and the patient subsequently underwent the indicated surgery. Patients in whom MR imaging–documented normal anatomy but whose paralysis did not improve by 3 months postinjury underwent surgery in which nerve repair was performed. In our experience, our MR imaging–based classification of root avulsion has provided valuable information for selecting the appropriate surgical procedure in patients with brachial plexus injury. Contributions provided by other specialists in diagnosing brachial plexus injuries with this technique and classification system will be useful.

References