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Three-dimensional MR Myelography of Traumatic Injuries of the Brachial Plexus

Roberto Gasparotti, Stefano Ferraresi, Lorenzo Pinelli, Mario Crispino, Marco Pavia, Matteo Bonetti, Debora Garozzo,Ornella Manara, and Antonio Chiesa

PURPOSE: To determine the diagnostic accuracy of three-dimensional MR myelography in the evaluation of traumatic injuries of the brachial plexus. **METHODS:** Twenty patients with clinical and electromyographic evidence of traumatic brachial plexopathy were examined with three-dimensional MR myelography, conventional cervical myelography, and CT myelography 1 to 9 months after trauma. Three-dimensional MR myelography was performed on a 1.5-T MR unit with a constructive interference in steady state (CISS) technique. For each patient, maximum intensity myelographic projections and multiplanar reconstruction reformatted 1-mm axial sections were obtained from the same 3-D data set. Three-dimensional MR myelographic findings were compared with findings at cervical myelography and CT myelography. Surgical findings were available for comparison in 13 patients. **RESULTS:** Three-dimensional MR myelography enabled detection of meningoceles with avulsed or intact nerve roots, partial or complete radicular avulsions without disruption of the thecal sac, dural sleeve abnormalities, and dural scars. Assuming cervical myelography and CT myelography as the standards of reference, 3-D MR myelography showed 89% sensitivity, 95% specificity, and 92% diagnostic accuracy in the evaluation of nerve root integrity. **CONCLUSION:** Three-dimensional MR myelography can show the majority of traumatic lesions that involve the proximal portion of the brachial plexus in a single rapid examination. On the basis of our findings, we propose this technique as a screening examination for patients with traumatic brachial plexus palsy.

Index terms: Brachial plexus; Magnetic resonance, three-dimensional; Spine, injuries

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Injuries to the brachial plexus result from road accidents and occur typically in young men involved in motorcycle accidents (1). Diagnostic imaging is important to locate the level of the injury, as prognosis and treatment planning greatly depend on differentiating complete (preganglionic) nerve root avulsion from lesions distal to the sensory ganglion (postganglionic) (2). Postganglionic lesions have a better prognosis, and acceptable motor function can be restored after neurolysis, neurorrhaphy, or nerve grafting, while in preganglionic lesions only partial motility can be restored with nerve transfer procedures (3). In nerve transfer or "neurotization," a healthy but less valuable nerve or its proximal stump is transferred in order to reinnervate a more important motor territory that has lost its function through damage to its nerve. Intraplexal neurotization consists of approximation of avulsed elements of the plexus onto the proximal stumps of spinal nerves ruptured outside the foramina but still attached to the spinal cord. In extraplexal neurotization, extraplexal nerves (intercostal, spinal accessory, branches of the cervical plexus) are transferred onto distal stumps in cases of multiple nerve root avulsions (4).

Despite the advent of magnetic resonance (MR) imaging, which has replaced other imaging techniques for evaluation of almost all dis-

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eases of the spine, conventional and computed tomographic (CT) myelography are still considered the first-choice examinations in the evaluation of traumatic injuries of the brachial plexus, since they provide good anatomic depiction of root sleeves and nerve roots, unachievable with conventional MR imaging, owing to the insufficient contrast between the subarachnoid space and neural structures, a problem that is caused by cerebrospinal fluid (CSF) pulsatility (5).

Three-dimensional MR myelography is a technique for generating myelogramlike images. It has been tested in a limited number of patients mainly for the evaluation of degenerative disease of the lumbar spine, generally without comparison with conventional myelography (6). Our aim was to assess the diagnostic accuracy of 3-D MR myelography in the evaluation of traumatic injuries of the brachial plexus.

Subjects and Methods

Between January 1993 and December 1994, 20 patients with traumatic brachial plexus injuries were examined at our institution. The group comprised 18 men and two women, ranging in age from 17 to 46 years (mean, 26 years). Sixteen patients had been involved in severe motorcycle accidents. All patients had clinical and electromyographic evidence of brachial plexus injury: 10 patients had a complete brachial plexus palsy, three had a subtotal brachial plexus palsy, four had an upper brachial plexus palsy (Erb-Duchenne), and three had a lower brachial plexus palsy (Dejerine-Klumpke). Thirteen patients underwent surgical exploration.

All patients were first examined with 3-D MR myelography 1 to 9 months after the injury, followed by conventional myelography, which was performed with injection of 10 mL of iodinated water-soluble contrast medium by lumbar puncture. CT myelography was performed 4 to 8 hours after intrathecal injection of the contrast medium. Contiguous 2-mm-thick axial scans from the fourth cervical to the second thoracic vertebrae were obtained with a high-resolution reconstruction algorithm.

MR examinations were performed on a 1.5-T superconductive unit equipped with a Helmholtz neck coil. Three-dimensional MR myelography was based on 3-D constructive interference in steady state (CISS) sequences (7) (M. Deimling, G. Laub, "Constructive Interference in Steady State [CISS] for Motion Sensitivity Reduction," in: *Book of Abstracts: Society of Magnetic Resonance in Medicine,* 1989:842–8497). CISS sequences derive from fast imaging with steady-state precession (FISP) sequences, in which T2* contrast is obtained in the steady state of longitudinal and transverse magnetization by using short repetition times ($<<$ T2) with large flip angles. With standard FISP sequences, however, the CSF signal is lower than expected, because the CSF flow, which is not constant in time, experiences continuous phase shifts while moving across field gradients, with consequent reduction of the transverse magnetization and failure to achieve the steady state (7). CISS sequences are designed to reduce CSF flow-induced phase shifts and to enhance the contrast between CSF and soft tissue. Flow compensation is applied to each gradient over each repetition time cycle so that all three gradients are balanced and no additional phase shifts are created by the application of gradient pulses. These sequences, called *true FISP*, are not sensitive to flow but are sensitive to magnetic field inhomogeneities, which are responsible for the appearance of bands of low signal intensity in the images. To overcome this problem, two different sets of images are acquired consecutively, the first one with radio-frequency pulses of the same phase and the second one with alternating phases, so that the dark bands are in different locations in the corresponding images. A single set of images with uniform signal intensity and high contrast between CSF and neural structures is finally obtained by taking the maximum signal between the two acquisitions on a pixel-by-pixel basis, with a simple mathematical algorithm (8).

Each 3-D CISS acquisition consists of a sagittal 64-mm slab with 64 partitions centered on the cervical spine, including the first three thoracic vertebral bodies. The following parameters were used: 14/21/1 (repetition time/echo time/excitations), 50° flip angle, 20-cm field of view, and 256 × 256 matrix. The acquisition time was 4 minutes for each sequence. The 3-D data set was then processed with a maximum intensity projection (MIP) algorithm in order to obtain myelogramlike images at multiple angles.

A limited region of interest was selected, containing the vertebral bodies, the thecal sac, and the nerve roots, with partial exclusion of paravertebral muscles and fat, which can obscure anatomic details. Since MIP artifacts can be responsible for inconstant visualization of nerve roots within the root sleeves on MIP views, 2-mm-thick reformatted axial oblique sections were then obtained from the same 3-D data set with the multiplanar reconstruction algorithm. The axial reformatted sections were oriented with a progressive increase of the angle with the intervertebral disk from C-4 to T-2 following the direction of nerve roots, which changes from C-5 to T-1. To formulate a correct diagnosis of nerve root avulsion, we simultaneously rotated the paraxial sections in two different planes to depict best their attachment to the spinal cord.

MIP myelogramlike projections were evaluated together with the multiplanar reconstruction reformatted axial oblique sections. 3-D MR myelograms, cervical myelograms, and CT myelograms were reviewed independently and blindly by two observers without knowledge of clinical, surgical, or electromyographic findings. The whole set of images was examined in order to identify the single nerve roots coursing in the subarachnoid space. A forced-choice decision about the presence or absence of nerve root avulsion was made independently by the two observers. Since potential errors in the interpretation of 3-D MR myelograms can derive from an MIP algorithm, a nerve root was considered completely avulsed from the spinal cord when

TABLE 1: Imaging findings in 20 patients with traumatic brachial plexopathy

3-D MR Myelography	Conventional Cervical Myelography			CT Myelography			Total
	Meningocele with Avulsed Roots	Root Avulsions without Meningocele	Intact Roots	Meningocele with Avulsed Roots	Root Avulsions without Meningocele	Intact Roots	
Meningocele with avulsed roots	23	3	1	26	0	1	**27**
Root avulsions without meningocele	0	7	2	0	7	2	**9**
Intact roots	3	2	57	2	0	60	**62**
Total	**26**	**12**	**60**	**28**	**7**	**63**	**98**

TABLE 2: Imaging and surgical findings in 13 patients with traumatic brachial plexopathy

Surgical Exploration	3-D MR Myelography		Conventional Cervical Myelography		CT Myelography		Total
	Avulsion (Complete-Partial)*	Intact Roots	Avulsion (Complete-Partial)*	Intact Roots	Avulsion (Complete-Partial)*	Intact Roots	
Avulsion (complete-partial)*	20	3	22	1	20	3	**23**
SEP avulsion	1	3	3	1	3	1	**4**
Stretch injuries	1	11	1	11	1	11	**12**
Intact	3	21	1	23	1	23	**24**
Total	**25**	**38**	**27**	**36**	**25**	**38**	**63**

Note.—SEP indicates somatosensory evoked potentials.
* Two nerve roots could not be evaluated with any imaging technique.

both ventral and dorsal roots were unrecognizable on either MIPs or on multiplanar reconstruction axial oblique reformatted images. Discrepancies between the two observers were resolved by consensus.

The diagnostic accuracy of 3-D MR myelography in the evaluation of nerve root integrity was calculated for 98 nerve roots in 20 patients, including C-5/T-1 nerve roots from the injured side, taking as the standard of reference cervical myelographic and CT myelographic findings. Two nerve roots were excluded from the analysis because epidural scar tissue did not allow the subarachnoid spaces to be seen with any imaging technique. Since potential misinterpretations can derive from irregular filling of the subarachnoid space by the contrast medium, discrepancies between cervical myelography and CT myelography were resolved by a conjoined review of the two examinations.

Thirteen of the 20 patients underwent surgical exploration of the brachial plexus with intraoperative recording of somatosensory evoked potentials (SEP). In these patients, imaging findings were compared with surgical findings. Plexus surgery was performed by two experienced neurosurgeons. We decided not to calculate the diagnostic accuracy of 3-D MR myelography on the basis of surgical findings, since exploration of the roots of the brachial plexus in all the neural foramina was not routinely performed in every patient, and SEP registration is subject to many variations, mainly from positioning of the electrodes and from artifacts.

Results

Good-quality 3-D MR myelographic examinations were obtained in 18 (90%) of the 20 patients; in the other two patients, image quality was degraded by motion artifacts. The best MIP views for evaluating the root sleeves and nerve roots were the 10° to 30° anterior oblique projections, which better displayed the root sleeves on the injured side. Poor-quality conventional myelograms with insufficient filling of the cervical thecal sac were obtained in three patients, whereas good-quality CT myelographic examinations were obtained in 100% of cases. T-1 nerve roots were not recognizable with any imaging technique in two patients.

A summary of imaging findings appears in Table 1. A comparison between imaging and surgical findings in 13 patients is shown in Table 2.

Three-dimensional MR myelography, cervical myelography, and CT myelography detected 32, 27, and 32 traumatic meningoceles, respectively (Fig 1). In four patients, imaging findings were normal. Five large meningoceles, clearly identified with 3-D MR myelography and CT myelography, were undetected with cervical

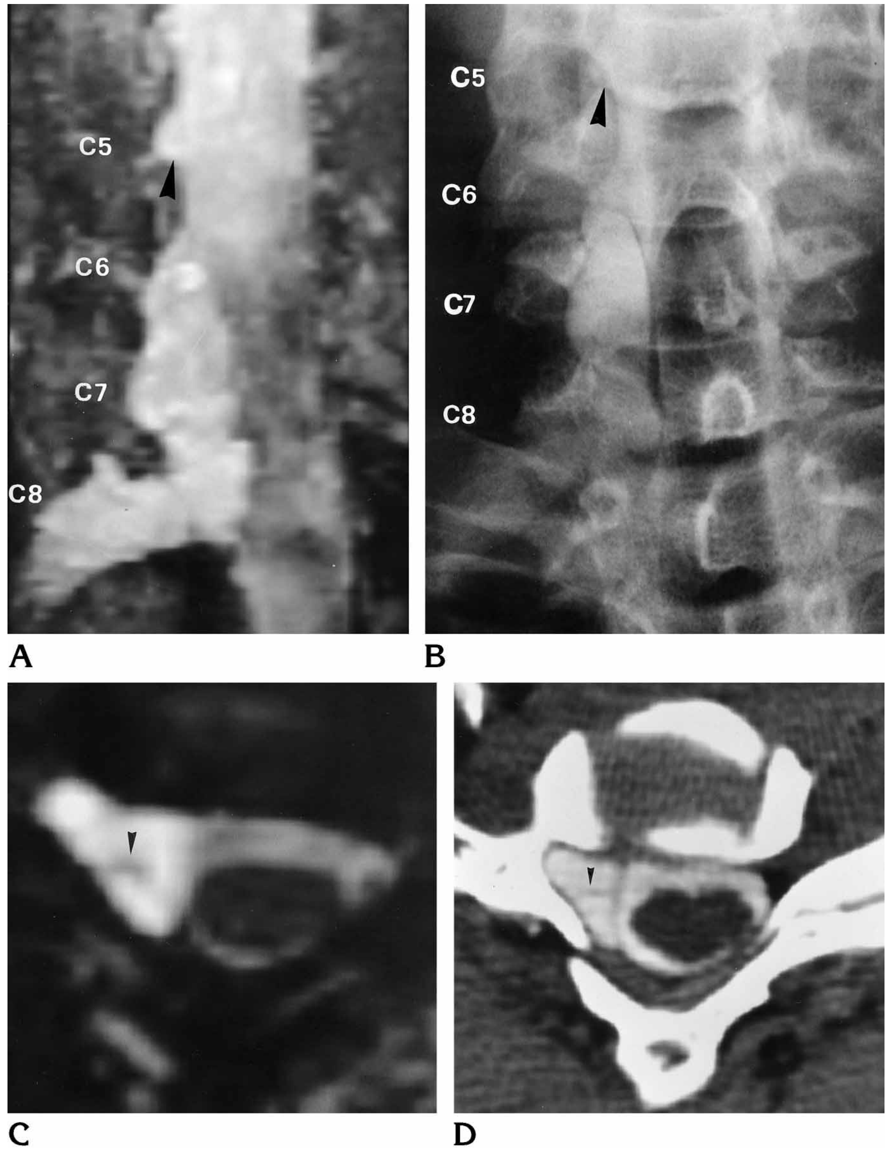

Fig 1. Complete right brachial plexus palsy.

A, Three-dimensional MR MIP myelogram, oblique view, shows C-5 avulsion with a small dural sleeve abnormality (*arrowhead*), large meningoceles at C-7 and C-8, and a poorly visible T-1 root sleeve. The C-7 meningocele reaches the C-6 root sleeve, but the C-6 nerve root is not identifiable.

B, On conventional myelogram, C-5 avulsion can only be suspected on the basis of poor concentration of contrast medium, while C-6 avulsion together with the C-5 dural sleeve abnormality (*arrowhead*) and the C-7 meningocele are confirmed. The C-8 meningocele and the T-1 root sleeve are poorly defined owing to inadequate filling with contrast medium.

C, Three-dimensional MR myelogram, axial reformatted image, shows right C-7 meningocele with a thin dark line corresponding to the C-7 avulsed nerve root, which is freely floating inside it (*arrowhead*). The signal intensity of the meningocele is higher than that of the thecal sac.

D, CT myelogram at the same level confirms the MR findings (*arrowhead*).

myelography; two of them were associated with extensive epidural scar. Five meningoceles with intact nerve roots were identified with 3-D MR myelography, three of which were confirmed with CT myelography (Fig 2), while an intact ventral root was missed in another meningocele, leading to a wrong diagnosis of partial avulsion. The meningoceles ranged in size from a few millimeters to 5 cm. Seven meningoceles had extradural extension to the paravertebral space and four had mass effect on the thecal sac. Three-dimensional MR myelography showed four root sleeve abnormalities on MIP myelograms, confirmed by cervical myelography, of which two were associated with complete nerve root avulsion and two with partial nerve root avulsion. Two root sleeve abnormalities without nerve root avulsion were missed with 3-D MR myelography, one of which was recognized only with cervical myelography. In the setting of asymmetric flat margins of the thecal sac, dural scar involving two levels was diagnosed in two patients at 3-D MR myelography and subsequently confirmed by cervical myelography. Thirty-four complete avulsions and three partial avulsions were detected with cervical myelography and CT myelography, 29 (78%) of which were associated with traumatic meningoceles. Four patients had avulsion of one root, six had avulsion of two roots, three had avulsion of three roots, and three had avulsion of four roots; four patients had no avulsions.

In the evaluation of nerve root integrity, 3-D

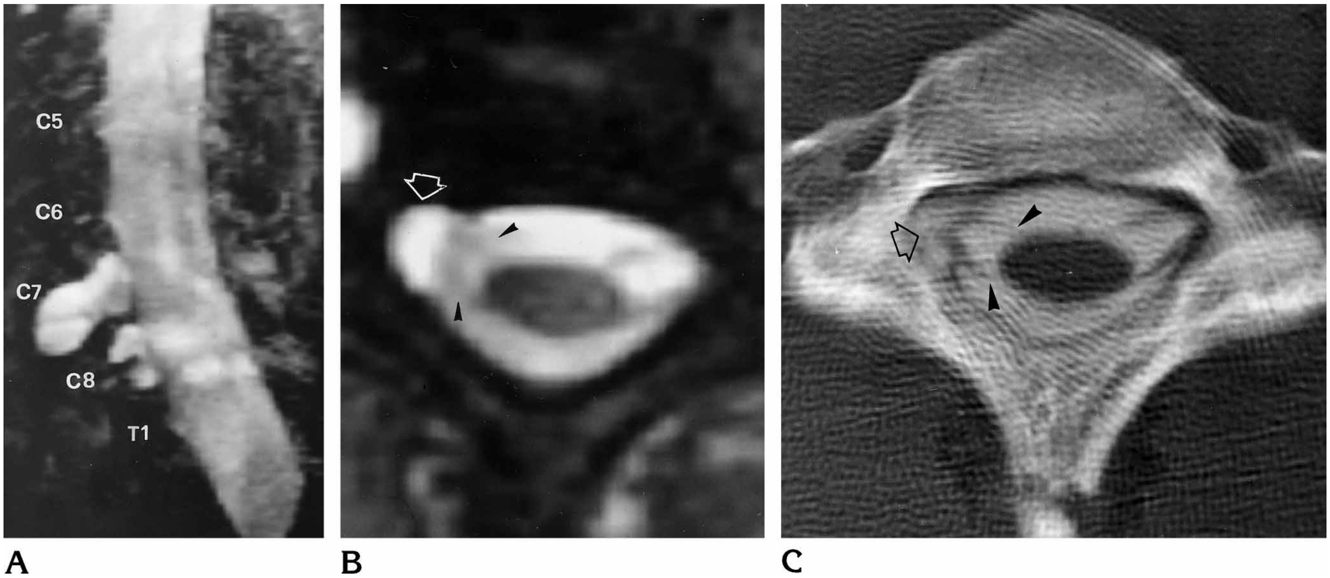

Fig 2. Complete right brachial plexus palsy.

A, On 3-D MR MIP myelogram, C-5 and T-1 are normal, C-6 is avulsed with a normal root sleeve, and C-7 and C-8 have meningoceles with absent roots.

B, Three-dimensional MR myelogram, reformatted axial image, shows right C-8 meningocele in the neural foramen (*open arrow*) with intact ventral and dorsal roots (*arrowheads*).

C, CT myelogram at the same level confirms the meningocele (*open arrow*) and the intact C-8 roots (*arrowheads*). A fracture of C-7 spinous process is also recognizable.

MR myelography showed 89% sensitivity, 95% specificity, and 92% diagnostic accuracy, with 33 true-positive findings, 58 true-negative findings, three false-positive findings, and four false-negative findings. Three-dimensional MR myelography, cervical myelography, and CT myelography matched exactly in 82 (84%) of 98 roots.

Three-dimensional MR myelography correctly showed five avulsions and two partial avulsions without meningoceles (Fig 3). The four false-negative findings consisted of three complete nerve root avulsions and one partial avulsion, two of which were also missed with CT myelography. The three false-positive findings represented two intact nerve roots, which were misinterpreted at 3-D MR myelography as completely avulsed (Fig 4) and by one intact root inside a traumatic meningocele, which was misjudged as partial avulsion. On axial reformatted images, the two readers were in agreement in classifying the nerve roots as avulsed or partially avulsed in 29 (81%) of 36 roots.

In the 13 patients who underwent surgical exploration of the brachial plexus, we found 24 intact roots (37%), 23 nerve root avulsions (35%), and two partial avulsions (3%), of which three were undetected with all three imaging techniques and two were undetected with 3-D MR myelography and CT myelography. Intraoperative SEP revealed four functional avulsions (6%) with macroscopically intact nerve roots with absent or reduced response to electrical stimulation: two nerve roots were considered normal and avulsed, respectively, on the basis of all imaging techniques; one nerve root that was thought to be attached to the spinal cord at 3-D MR myelography was seen as avulsed at cervical myelography and CT myelography; and one nerve root that was believed to be attached to the spinal cord at 3-D MR myelography was considered avulsed at cervical myelography and partially avulsed at CT myelography. Twelve pure "stretch injuries" were found at surgical exploration (19%). In one of these, all three imaging techniques showed a meningocele with root avulsion; in a second case, 3-D MR myelography and CT myelography showed a meningocele with an intact root; and in a third case, 3-D MR myelography and cervical myelography depicted a dural sleeve abnormality with an intact root. In the remaining nine cases, the roots appeared intact on all imaging techniques.

Discussion

Traumatic injuries to the proximal portion of the brachial plexus are characterized by a wide

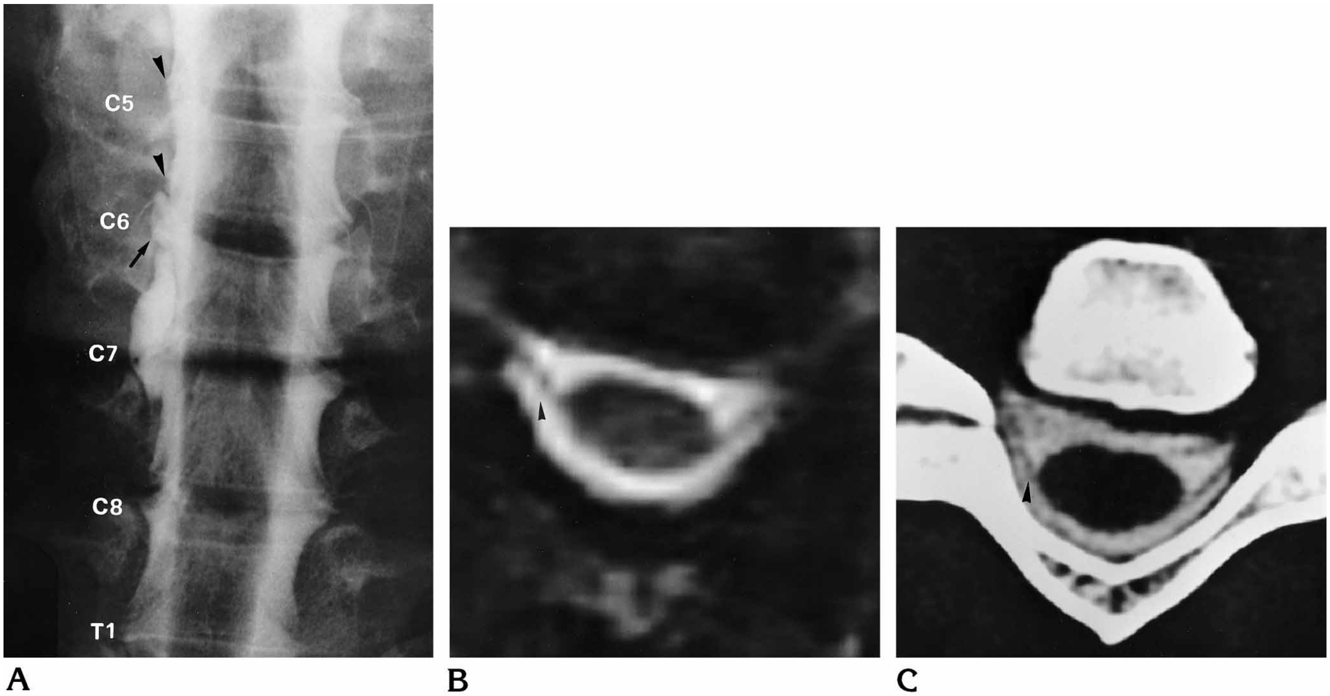

Fig 3. Upper right brachial plexus palsy plus C-7 meningocele.

A, On conventional myelogram, the right C-5 and C-6 nerve roots are diminished in size (*arrowheads*), suggesting partial avulsion, while C-8 and T-1 are normal. C-6 root sleeve abnormality (*arrow*) and C-7 meningocele with avulsed roots are also recognizable.

B, 3-D MR myelogram, reformatted axial image at C4–5. On the right side, only the dorsal root is identifiable within the root sleeve (*arrowhead*), while on the contralateral side, the ventral and dorsal roots are both recognizable. Right C-5 partial avulsion is therefore suspected.

C, CT myelogram at the same level confirms right C-5 partial avulsion (*arrowhead*), since the ventral root, compared with the contralateral side, cannot be followed in its course from the spinal cord to the neural foramen.

range of abnormalities of the thecal sac, caused by maximum stress occurring at the site of nerve root attachment to the cord. These abnormalities include traumatic meningoceles, deformity of nerve root sleeves, dural scar, and nerve roots avulsions (9). The most common lesions are traumatic meningoceles, which are bulges of the arachnoid membrane through a dural tear (10). The vast majority of nerve root avulsions are associated with traumatic meningoceles, and for many years the radiologic diagnosis of nerve root avulsion relied on the identification of meningoceles, although nerve root avulsions with no dural abnormalities have been well documented (11, 12).

The preoperative diagnostic workup must focus on the assessment of nerve root integrity, because of the possibility of using the root for nerve repair and reconstruction of the plexus (13). Despite its invasiveness, cervical myelography alone or in conjunction with CT is still considered the first-choice examination, even with its potential for false-positive and false-negative findings, owing to either inadequate concentration of contrast material or incorrect orientation of CT scans (14–16).

The advent of MR imaging has not modified the diagnostic approach to traumatic brachial plexus injuries. MR imaging is suitable for demonstrating the anatomy of the brachial plexus, as it reliably shows roots, trunks, and cords together with muscles and vessels, but MR imaging has been insufficient for the demonstration of nerve root avulsions, which require high contrast between CSF and soft tissue, which is usually not obtainable with conventional T2- or T2*-weighted imaging (17–21). In our study, however, 3-D MR myelography was superior to cervical myelography in the identification and anatomic depiction of traumatic meningoceles, which typically appeared as elongated lobulated lesions in the neural foramina, often extending and mushrooming into the paravertebral space. Three-dimensional MR myelography, unlike conventional myelography, does not rely on filling of subarachnoid spaces by contrast medium and it is able to show the meningoceles when there are some obstacles to

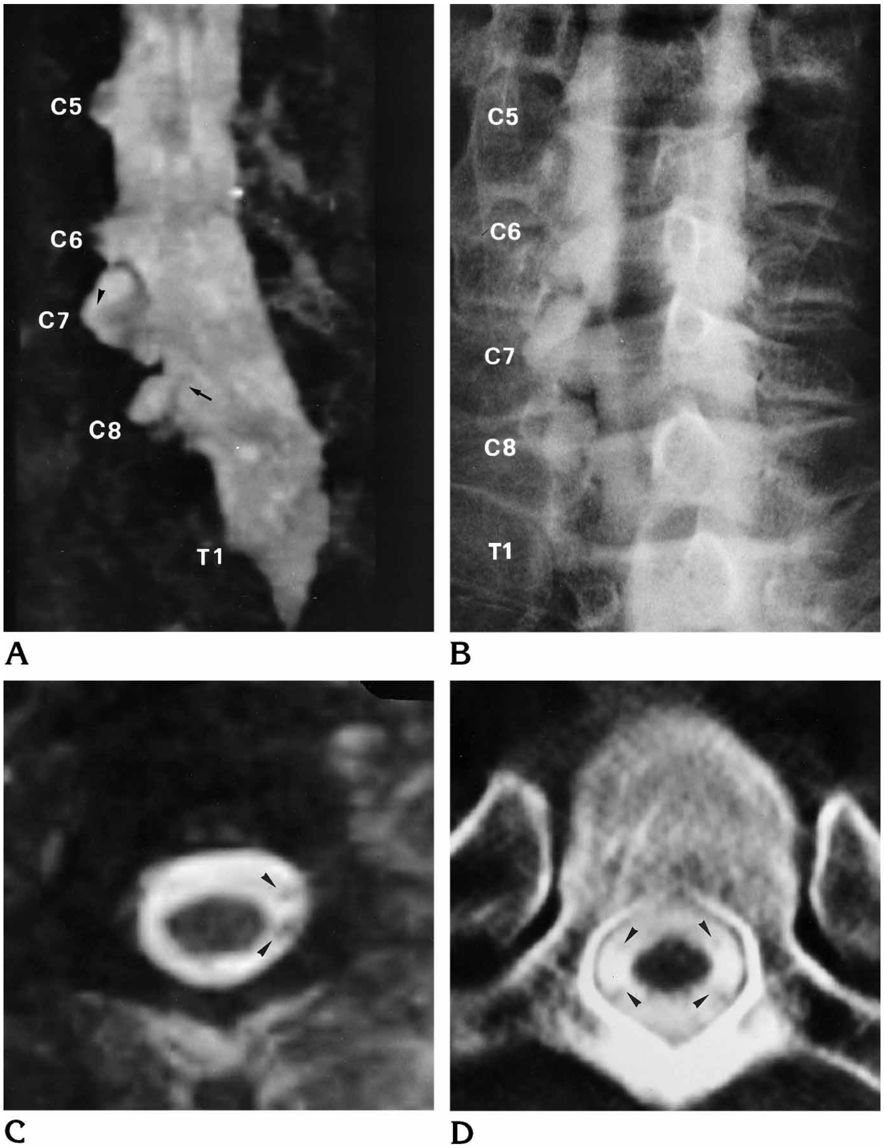

Fig 4. Right upper brachial plexus palsy.

A, On 3-D MR MIP myelogram, C-5 is normal. The C-6 root sleeve is irregular; however, the C-6 nerve root is visible. Two meningoceles are identifiable at C-7 and C-8, with a C-7 avulsion and an intact C-8 root (*arrow*). The abrupt ending of the C-7 root is recognizable (*arrowhead*). T-1 seems to be avulsed.

B, On conventional myelogram, the C-6 root sleeve abnormality and C-7 meningocele with absent roots are confirmed, while the C-8 meningocele and the T-1 root sleeve are poorly delineated.

C, 3-D MR myelogram, reformatted axial image, at T1–2. On the right side, the T-1 ventral and dorsal nerve roots are not identifiable, whereas the contralateral nerve roots are well displayed (*arrowheads*). This is an example of a false-positive finding of avulsion, since the right T-1 nerve roots were subsequently identified at CT myelography (*D*).

D, CT myelography at the same level shows T-1 nerve roots on both sides (*arrowheads*).

penetration of contrast medium, such as small necks or surrounding epidural scar. On reformatted axial 3-D MR myelographic images, the size, shape, and extension of the meningoceles were comparable to CT myelography, which is generally recognized as being superior to conventional myelography in the detection of traumatic meningoceles (22, 23).

Large multilocular meningoceles can be recognized also by conventional MR imaging (24, 25); however, their full extension within the spinal canal can be assessed better on 3-D MR myelographic MIP views, since they are characterized by signal intensity higher than normal subarachnoid spaces, due to either very slow CSF flow or higher protein content (see Fig 1).

Compared with cervical myelography and CT myelography, which are considered the standards of reference, 3-D MR myelography showed 89% sensitivity, 95% specificity, and 92% diagnostic accuracy in identifying nerve root avulsion.

Nerve root avulsions without or with small dural sleeve abnormalities are well demonstrated by cervical myelography, and are reported in the literature as constituting 13% to 20% of nerve root injuries (15). In our study, they represented 21% of injured roots, and 3-D MR myelography was able to show 75% of such lesions with good anatomic correlation with cervical myelographic findings (see Figs 1A and 2A).

Three-dimensional MR myelography also allowed the detection of two (67%) of three partial

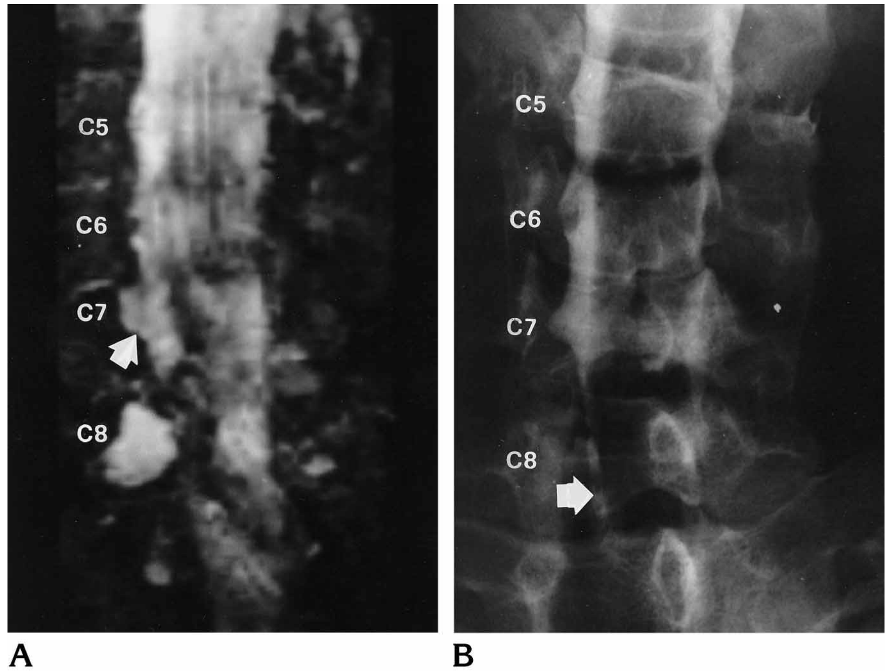

Fig 5. Complete right brachial plexus palsy.

A, On 3-D MR MIP myelogram, C-5 nerve root shadows are slightly reduced in size (partial avulsion), C-6 is normal, C-7 is avulsed with a small root sleeve abnormality (*arrowhead*). C-8 has a meningocele and, at T-1, the root sleeve is not identifiable. The incomplete visibility of the right thecal sac border from C-7 to T-1 suggests the presence of epidural scar.

B, Conventional myelogram confirms the 3-D MR myelographic findings at C-5, C-6, and C-7. The C-8 meningocele is completely overlooked owing to epidural scar, which causes the right thecal sac border to appear irregular and poorly defined (*arrow*).

avulsions on axial reformatted images as absence of the ventral nerve root together with a recognizable dorsal nerve root in continuity with the spinal cord (see Fig 3). Partial avulsions must be recognized preoperatively because they cannot be used in nerve transfer procedures and might be erroneously interpreted as normal on the basis of both intraoperative SEP and surgical findings (26).

Conventional MR imaging proved to be highly sensitive in detecting nerve root avulsion in the only study in which it was compared with cervical myelography, CT myelography, and surgical findings in this regard (27). In that study, however, MR imaging was performed with T1-weighted spin-echo sequences, which resulted in poor contrast between nerve roots and subarachnoid spaces, and with a 5-mm section thickness, which represents a potential source of error owing to partial volume effects. That study also revealed a limitation of CT myelography; namely, that it can depict only small segments of the root sleeves and not their entire course, thus creating the potential for a false-positive diagnosis of disconnection of the nerve roots.

The identification of intact nerve roots inside a meningocele can be difficult with either cervical myelography or CT myelography when the contrast medium inside the meningocele is insufficient. Nerve roots can be avulsed from the spinal cord but still remain floating in the meningocele: in such a case, the disconnection must be clearly demonstrated (see Fig 1C and D). In our study, 100% of the intact nerve roots within traumatic meningoceles were recognized by 3-D MR myelography, even though one completely and one partially avulsed nerve root were judged as normal. Intact roots within the meningoceles are seen better on axial reformatted sections, which, if accurately oriented, depict ventral and dorsal roots as thin hypointense bands connected to the spinal cord and crossing the meningocele in the neural foramen (see Fig 2B and C). In none of the articles reporting MR imaging evaluation of nerve roots in traumatic injuries of the brachial plexus were there comments on the possibility of visualizing intact nerve roots inside the meningoceles (27, 28).

Epidural scar, which is recognized at myelography as a filling defect in the dural sac, was observed in two patients and appeared at 3-D MR myelography as an irregular and discontinuous lack of signal intensity of the thecal sac border. In the presence of a dural scar, conventional myelography can overlook small meningoceles, which do not fill with contrast medium and are, on the contrary, well demonstrated with 3-D MR myelography (Fig 5).

One of the major disadvantages of 3-D MR myelography was CSF flow artifacts, which were more prominent at the cervicothoracic junction and in areas of narrowed subarachnoid space. The result can be a reduction in contrast between nerve structures and subarachnoid space, with consequent poor visibility of nerve roots that may be erroneously interpreted as avulsed. This fact can account for the observed false-positive and false-negative findings (see Fig 4). 3-D MR myelography is also subject to motion artifacts, even though the short examination time allowed us to obtain diagnostic examinations in all cases.

In the 13 patients who underwent surgical exploration, we encountered some discrepancies between surgical and imaging findings, which have been well documented in the literature (29). For example, it is known that intraoperative SEP recordings are subject to artifacts, and surgical exploration likewise has potential sources of errors, such as anatomic distortions induced by trauma and fibrotic plexus, in which the lower avulsed roots are not identified. Such potential errors must be discussed in light of the MR findings.

One limitation of this study is that cervical myelography was done by lumbar puncture, the disadvantage of which includes poor concentration of contrast medium in the meningocele or in the root sleeves. We compensated for this effect by combining conventional myelography with CT myelography, which better delineates meningoceles and nerve roots in areas where concentration of contrast material is poor. Cervical myelography with direct puncture of C1–2 would be a better alternative, since the filling of the thecal sac is optimal, but its risks are higher, especially in patients with traumatic injuries who cannot stay comfortable in a prone position (30, 31).

Another limitation of the study is that we did not compare 3-D MR myelography with conventional T2-weighted axial spin-echo imaging or with 3-D gradient-echo axial imaging of the spine to investigate their advantages and disadvantages in the evaluation of nerve roots. Moreover, at the time the study was initiated, we did not have the availability of fast spin-echo sequences, which have recently proved to be suitable for MR myelography owing to their excellent spatial resolution, which is based on 512 matrices and therefore superior to that of CISS sequences (28, 32).

In conclusion, we found 3-D MR myelography to be useful for the initial screening of patients with traumatic injuries of the brachial plexus. The amount of information provided by this technique is comparable to that obtained with cervical myelography or CT myelography. The high degree of sensitivity and specificity favors 3-D MR myelography as the examination of first choice. Cervical myelography and CT myelography could then be performed only in those cases in which discrepancies were found among the clinical, electromyographic, and 3-D MR myelographic findings or when the quality of the examination was poor. With further improvement in spatial resolution and compensation for CSF flow pulsatility, we can expect further advances in this technique.

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