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Current advances in magnetic resonance imaging (MRI) in spinal cord trauma: review article

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Magnetic resonance (MR) images of 87 patients who had sustained spinal cord injuries during the past 2 years, were analyzed and compared with the corresponding clinical, surgical, and in some cases pathological findings. In addition to the standard MR imaging techniques applied in the spinal cord injuries, we also introduced some recent MRI technical achievements which are anticipated to improve diagnostic accuracy and broaden clinical application of this modality with regard to the spinal cord trauma. The recent technical advancements that we used include image enhancement, fat tissue signal suppression, three-dimensional (3-D) imaging, and magnetic resonance angiography (MRA). The reviewed post traumatic changes disclosed in these MR images were classified in 4 categories: acute, subacute, chronic, and the injury's sequelae. The essential properties of the 4 new imaging advancements are considered in relationship to the gain in diagnostic improvement of MRI of the 4 phases of patients with spinal cord trauma.

Key words: spinal cord trauma; magnetic resonance imaging (MRI); new techniques.

Introduction

Some well recognized characteristics of magnetic resonance imaging (MRI) of the spinal cord demonstrate that this diagnostic modality has certain advantages over other neuroimaging techniques.[1-4] Among these advantages of significance for the evaluation of an injured spine and spinal cord are the excellent contrast resolution of MR images, the absence of bone artifacts, the feasibility of multiplanar imaging without changing the patient's position, and the choice of different pulse sequences which intensify the anatomical detail and contribute to MRI sensitivity[5-9] (Fig 1). Yet, it is also important to recognize the existing limitations that affect the diagnostic accuracy of MRI in spinal cord trauma.[10] They include the rather long imaging time during which the patient is asked to remain motionless in the required position. Furthermore, the imaging may be impeded by certain supporting devices (traction, intubation, anesthesia equipment, etc), or it may turn out unproductive. In addition, MRI cannot always provide the diagnosis of the type of lesion, and the separation of the basic lesion from perifocal edema is, at best, difficult with MR images.[11-13] Also, MRI does not offer in all cases information about necrotic or calcified areas or vascular anomalies related to the injury, and, on occasion, the sensitivity of MRI is suboptimal, thus the presence of a traumatic lesion of the spinal cord can remain uncertain.[14,15] But despite these insufficiencies, one can say that MRI is the best neuroimaging technique for the evaluation of spinal cord injury that we have at present. It is superior to high resolution computed tomography (CT) or delayed metrizamide CT, and as accurate as intraoperative sonography.[16] However, MRI can be performed as many times as necessary, even on an outpatient basis, without known hazards or major discomfort to patients, which is not the case with intraoperative sonography.

Since its introduction into clinical practice, MRI has been continuously undergoing technical improvements, which have step by step brought its diagnostic accuracy to a

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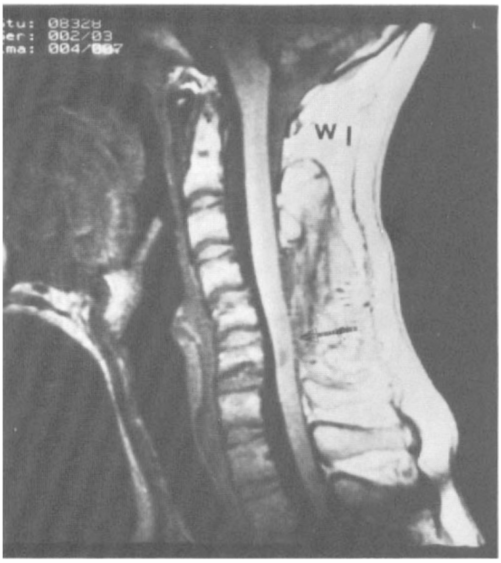


Figure 1 The saggital MR image shows a deformity of the C5–C6 vertebrae, and a large defect of the posterior cervical wall at the myelotomy site. There is a cylindrically shaped lesion of low signal intensity, indicated by the arrow, in the cervical spinal cord substance, representing a post traumatic cyst. The outstanding contrast seen in this image is one of the main features of MRI.

high level. Among recent technical advancements, 4 are important in our view for the evaluation of patients with spinal cord injuries: namely, image enhancement, signal suppression, three-dimensional (3-D) imaging and magnetic resonance angiograghy (MRA).

We would like to describe the main features of the above mentioned 4 MR imaging advancements without entering into detailed analysis of their physical properties, which is not the purpose of this paper. Also, we wish to correlate, within the amount of space allocated to us, MRI findings obtained by means of these advances, with the pathological picture of a spinal cord injury in the acute, subacute, chronic and final (sequelae) phases.

In summary, the pathological findings of acute *blunt injury* to the spinal cord point to the occurrence of hemorrhage and edema within the central cord mostly at the level of impact. The disruption of the vascular network results in the impairment of blood flow, petechial hemorrhages, and alteration of the blood-brain barrier. If the dura is lacerated the swollen spinal cord can extrude through the defect. In addition, a nerve root avulsion or fracture of the bony elements or discs can be present as well as epidural hematoma. In general the severity of the trauma will depend upon the area of impact, velocity, mass, and whether the spinal column was fixed or movable at the moment of injury. *Penetrating injuries* (caused by bullets, knives, flying glass, metal or bony fragments, etc) range from small lesions to hemisection or transection of the spinal cord, and the amount of hemorrhage will depend upon the extent of damage to blood vessels. Fractures of the bony components of the spine and discs, laceration of the meninges, and damage to the nerve roots are commonly encountered. Both types of injuries in the subacute phase lead to central necrosis which appears within hours to days, and degeneration of the white matter tracts which continues over a period of weeks. In the later phases changes which tend to become permanent take place such as cavities in the spinal cord, from single to multiple, resulting in post traumatic syringomyelia, and gliosis localized or diffuse, and also atrophy, adhesions, osteomyelitis and occasionally abscess formation, thrombosis of the feeding arteries, post traumatic arterio-venous shunts, etc.[17]

For the past 2 years we have analyzed the appearances of pathological changes in post traumatic MR images of 87 patients, and have assessed the effects of the new imaging techniques now available.

Methods

Paramagnetic enhancers

The first paramagnetic enhancer used in clinical practice (since June 1988, in the USA) is gadolinium diethylenetriamino-penta-acetic acid (Gd-DTPA). Later, other pharmaceutical compounds of gadolinium have been introduced, for example gadopentetate dimeglumine, which we have been using commonly so far. Apart from gadolinium there are quite a number of other substances that have an MR enhancing ability, and we should expect in the future the introduction of various MRI enhancers, in particular for MRA.

The paramagnetic substances differ in their nature from iodinated contrast media which provide image contrast by direct action. An increase in concentration of the contrast medium causes an increase in the image contrast. Conversely, the paramagnetic substances have the ability to enhance the relaxation process of adjacent protons. This enhancement results from the interaction of protons with unpaired electrons of the paramagnetic substance. In this process the paramagnetic enhancer itself is not imaged.[18,19] Consequently, paramagnetic enhancers have an indirect effect on the image contrast. It should be noted that in high concentrations the action of paramagnetic enhancers may be minimal or reversed, a phenomenon known as 'negative enhancement'.

Gadolinium proved to be very suitable for clinical studies because of its marked effect on proton relaxation, its stability, rapid renal clearance, and its good tolerance by patients. Yet, it can cause a transient increase in serum iron concentration, which is observed in about 20–30% of patients, as well as a rise in serum bilirubin, though in a smaller number of patients. Both changes were of short duration without noticeable clinical sequelae. The presently used dose is 0.1 to 0.2 mmol/kg, although we obtained satisfactory enhancement even with a dose of 0.05 mmol/kg.

Two biological properties of Gd-DTPA should also be mentioned. The distribution of Gd-DTPA is extracellular, and under normal conditions it does not cross the blood-brain barrier, a phenomenon that should be considered in the process of analyzing post traumatic MR images of the spinal cord. For further information concerning the biological effects of gadolinium, we wish to refer the reader to some research work which elucidates this matter in a more detailed way.[20–24]

The application of Gd will usually enhance the image of an acute intramedullary hematoma. Subacute hematomas appear mostly intense with or without Gd enhancement, and a dark halo may be seen in the periphery of a chronic hematoma (Fig 2).

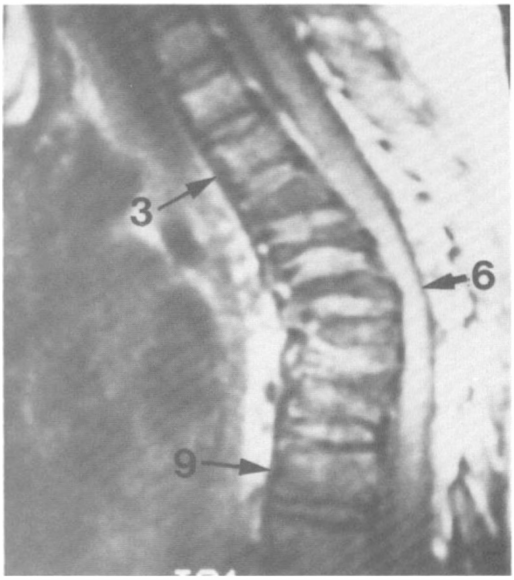


Figure 2 Two hours following injury in a motor vehicle accident (MVA) this sagittal image of the thoracic spine was obtained with Gd enhancement. The patient developed paraplegia immediately after the accident. The image demonstrates fractures of T5–T6–T7 and also T3 and T9. Kyphotic deformity in the mid thoracic spine is compromising the spinal canal and impinging on the cord. The hyperintensity in the spinal cord at the level of compression (arrow at 6) indicates the presence of enhanced hemorrhage. There is considerable swelling of the cord above and below the T6–T7 area, with a visible expansion of hemorrhage.

Furthermore, acute post traumatic spinal cord contusion becomes more evident if Gd is used. The presence of blood can be associated with myelomalacia, and in this situation Gd may be helpful in dissociating the 2 lesions (Fig 3). Furthermore, the Gd enhancement provides, in most instances, additional information about the presence and expansion of an epidural hematoma and its relationship to the spinal cord (Fig 4). The enhancement with Gd of the sequelae of spinal cord injuries may prove to be rewarding by making cavities or gliosis more distinct in post traumatic multiloculated syringomyelia (Fig 5), or the presence of a single cavity. The enhancement of epidural scars and of localized or diffuse meningeal adhesions is mostly of an informative

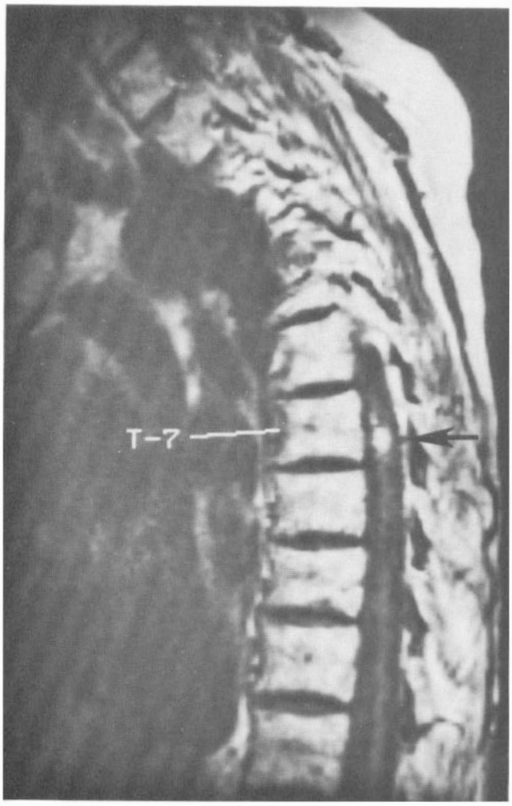


Figure 3 After a stable clinical period, following a thoracic spinal injury in a motor vehicle accident (MVA), the patient developed paraparesis of the lower extremities. The sagittal MR image with Gd enhancement depicts at the level of the T7 vertebral body a focal lesion with the characteristics of an old blood accumulation encircled by a poorly defined clear zone representing myelomalacia (arrow).

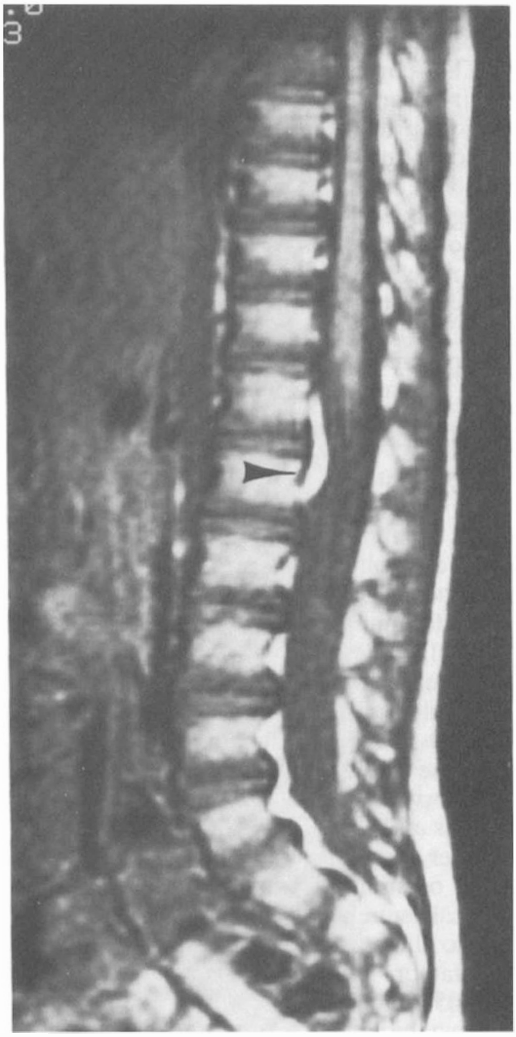


Figure 4 At the T12–L1 level (arrow) in this T-1 enhanced sagittal MR image of the thoracolumbar spine, an epidural hematoma is clearly outlined. The hematoma is compressing the ventral thecal sac. There is some faint appearance of Gd in the conus indicating the possibility of a contusion. The patient sustained an injury of the spine in a MVA.

nature.[25] The differentiation between the spinal nerve root sheath and scars is more reliable in Gd enhanced than in unenhanced MR images.[26]

On the basis of our present experience with the application of gadolinium compounds in spinal cord injuries, we think that in order to obtain the maximal benefit from enhancement patients should be very carefully selected. We do not apply gadolinium systemically, but prefer first to consider the use of appropriate pulse sequences and suppression techniques.[12,25–30]

Signal suppression

The presence of fat tissue in and outwith the spinal canal can interfere with image enhancement. That is, signals originating from fat tissue can cause a similar contrast intensity as a gadolinium enhanced lesion. Hence, both tissues will appear isointense in

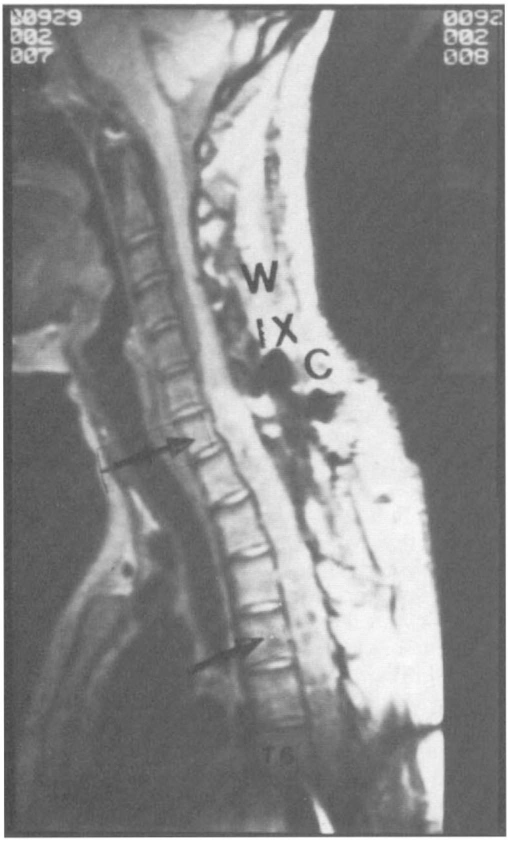


Figure 5 This sagittal Gd enhanced MR image of the cervical and upper thoracic spine of a patient who had a severe injury and required surgical treatment about 2 years ago, depicts atrophy of the spinal cord from the cerivco-medullary junction to the level of the C5 vertebra. From that level the spinal cord is noticeably dilated to the sixth thoracic vertebra. The subdural space is virtually obliterated by the expanded cord in the substance of which one can see a cavity with multiple separations, characteristic of multiloculated syringomyelia (arrows). At the level of C6 there is an increase of signal intensity consistent with enhanced gliosis (upper arrow). The postoperative defect of the posterior cervical wall is well defined.

the images, and the differentiation of the lesion in the spinal cord from fatty tissue will be difficult, if not impossible. To overcome this problem in the imaging of patients with spinal cord injuries, it may be rewarding to apply the fat suppression sequences with or without gadolinium enhancement. Such a fat suppression technique is expected to produce a selective reduction of the fat tissue signal intensity, without affecting the signal intensity of post traumatic lesions of the spinal cord. In fact, by using fat suppressing techniques, the characterization and delineation of a lesion should be improved.

There are different fat suppression techniques introduced for MR imaging which can be applied to the investigation of the injured spine and cord. Fat suppression can be accomplished with a frequency-selective presaturation pulse,[31] or with a hybrid technique used for solvent suppression in proton spectroscopy with the chopper fat suppression sequence.[32,33] The chopper fat suppression technique can be regarded as a real-time Dixon technique.[34]

An effective and relatively simple method of fat suppression is the hybrid sequence that does not require an increase in acquisition time. It does require, however, the adjustment of some parameters. Improper adjustment of these parameters may impede the process of fat suppression. The optimal fat suppression with the chopper sequence depends upon a good static field homogeneity, and represents a more complex procedure. In summary, by reducing the chemical-shift misregistration artifact the fat suppression sequence can increase the contrast between the fat tissue and high signal intensity lesions such as a subacute hemorrhage in the injured spinal cord.[35–37]

We have achieved good results in the evaluation of spinal cord injuries. For example, we have been able to delineate clearly, even without gadolinium, the presence of spinal cord contusion, hemorrhage, or compression by fractured vertebrae (Fig 6). The relationship between the spinal cord and extruded fragments of ruptured discs or injured vertebrae was obvious (Fig 7). Also, the damage caused to spinal nerve roots and the presence of epidural bleeding could be recognized by applying the fat suppression method (Fig 8). The imaging of post traumatic gliosis, scars and fibrotic changes associated with the surgical treatment of an injured spine and cord, with or without gadolinium, was informative in fat suppression MR images (Fig 9).

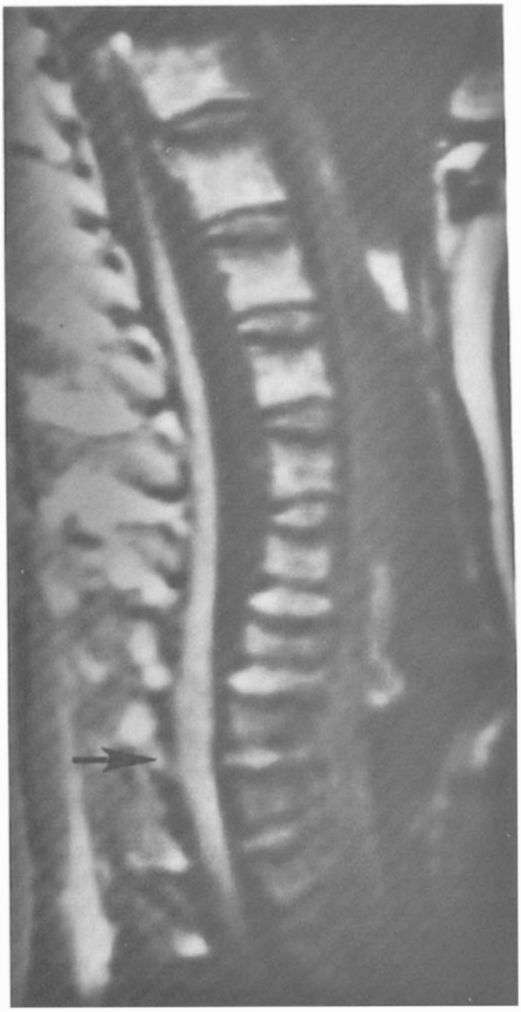


Figure 6 The sagittal T-1 MR image of the cervical and upper thoracic spine obtained with the fat suppression technique. The image is from a 12 year old male who had a severe fall, causing a hyperflexion injury of the neck. Swelling of the spinal cord from C3 to C5 (arrow) is clearly outlined and is compatible with cord contusion. In addition, the fracture of the C5 vertebra is evident. No gadolinium enhancement was applied.

Figure 7 Following a motor vehicle accident (MVA) this MRI was performed with the fat suppression technique in a female patient. A post traumatic herniated nucleus pulposus at the C6–7 level is clearly outlined with a large fragment of disc which has migrated superiorly and overlies the body of C6. The cervical cord at that level is compressed to a transverse diameter of approximately 6 mm. At the site of the compression there is an increase in signal indicating the presence of spinal cord contusion. No gadolinium enhancement.

Although the experience with fat suppression methods is, at this time of writing, relatively limited, it is our impression that its implementation in the process of the evaluation of spinal cord injuries has its merit. It provides informative images of a traumatized spinal cord without the necessity of the injection of gadolinium in many instances, which may facilitate the examination of paraplegic or quadriplegic patients, especially in view of the fact that these patients often require multiple follow up imaging examinations. However, as we indicated earlier, further improvements on fat suppression techniques are needed to upgrade and broaden the clinical application of this diagnostic modality with regard to spinal cord injuries.[38,39]

Three-dimensional MRI

Not long ago the possibility of three-dimensional (3-D) or volume-acquired imaging became available, representing a major advancement in MR technology. In the near future it may supersede the presently used two-dimensional (2-D) display of anatomical structures of the spine, which in reality has 3 dimensions.

The essential difference between the 2

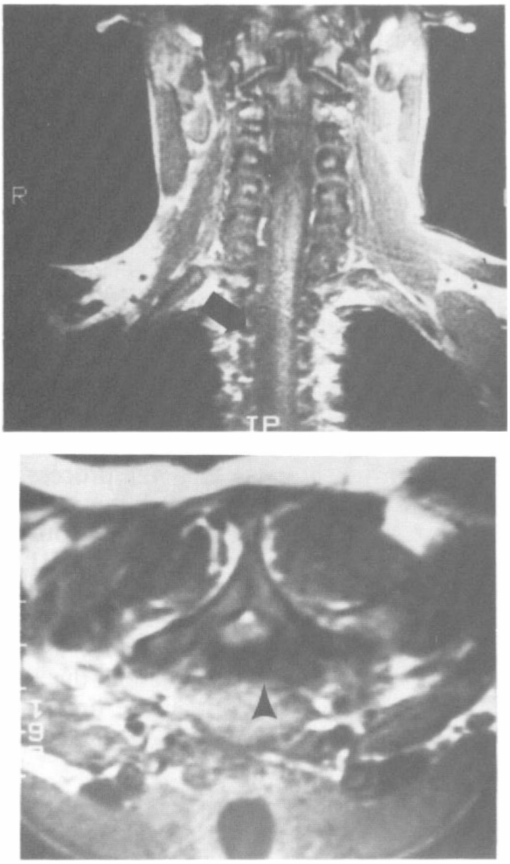


Figure 8 MR images of the thorax and cervical area obtained with the fat suppression method without enhancement, of a 15 year old male with the history of a motor vehicle accident (MVA). On admittance to hospital he complained of right upper extremity weakness. The coronal and axial images show a widening of the subarachnoid space (arrows) on the right side, approximately from C6 to T3 level. There is clear evidence of compression and displacement of the cord to the left side. These findings were compatible with avulsion and effusion of cerebrospinal fluid. At surgery, apart from the cerebrospinal fluid leakage related to the nerve avulsion, a larger amount of blood was also found, resulting from the laceration of a small artery.

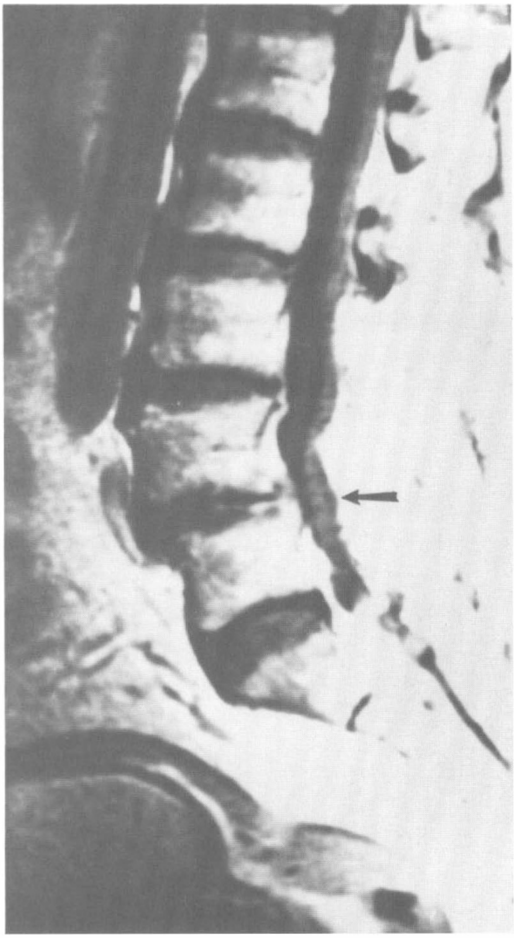


Figure 9 The MR image in sagittal projection, enhanced with gadolinium and the fat suppression method, of a female patient who was injured 2 years ago in a MVA. She had several fractures of the lumbar vertebrae, and had 2 post traumatic laminectomies. Her main complaints at the time of this examination were pain and weakness of the lower extremities. The MRI disclosed stenosis of the lumbar spinal canal with thick layers of scar tissue covering the dorsal wall of the spinal canal and expanding into the thoracic area (arrow).

imaging methods is that the 3-D technique has the capability to collect MRI data from the entire volume of the region rather than from a single scan at a time, as is the case with 2-D imaging. Furthermore, the data obtained can be reformatted so that one can see any part of the examined area from any angle. Using the 2-D method each image of a different plane must be reconstructed from a single scan. It is expected that the 3-D MRI will provide high resolution pictures of the pathological process in all dimensions from a single acquisition, which means that the present long MRI time will be greatly shortened, thus eliminating a major disadvantage of MRI imaging.[40] These features of 3-D imaging are of special interest for the evaluation of spinal cord injuries.

It should be mentioned that the 3-D imaging modality is not new and has been used for research purposes for a long period of time, but much experimental work was necessary to combine the fast gradient-echo sequences, advances in computer processing, and high magnetic field strength in order to bring 3-D imaging into clinical practice.

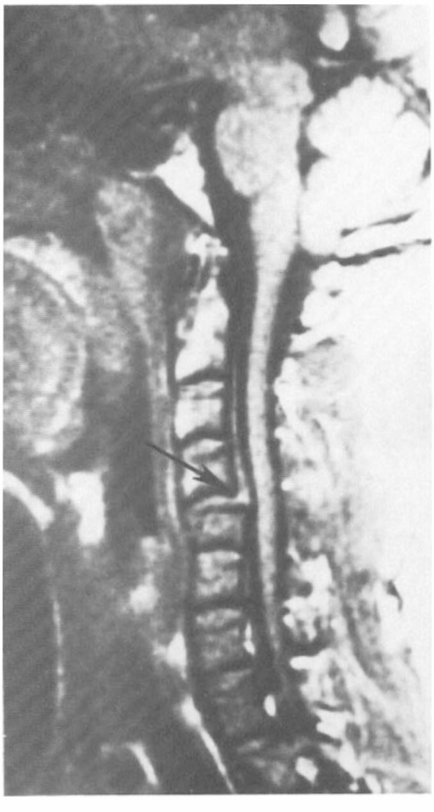
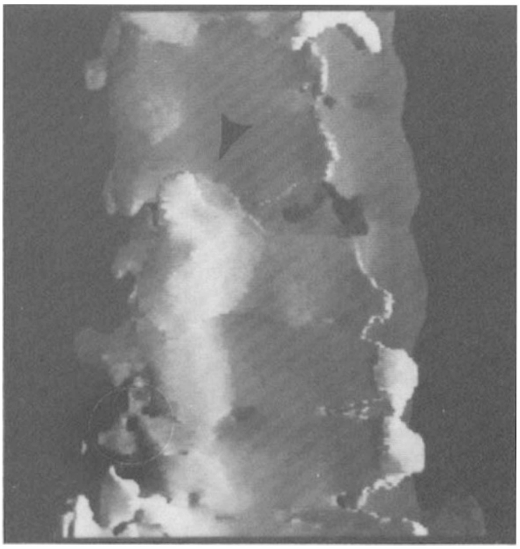


Figure 10a Following a MVA: subluxation of the cervical spine on admittance to hospital. The sagittal Tl image of the cervical spine reveals a disc fracture with extrusion of fragments at the C4–C5 level and dislocation of these vertebrae. An extensive epidural hemorrhage elevating the posterior longitudinal ligament is evident (arrow). The spinal cord appears to be displaced towards the dorsal wall.

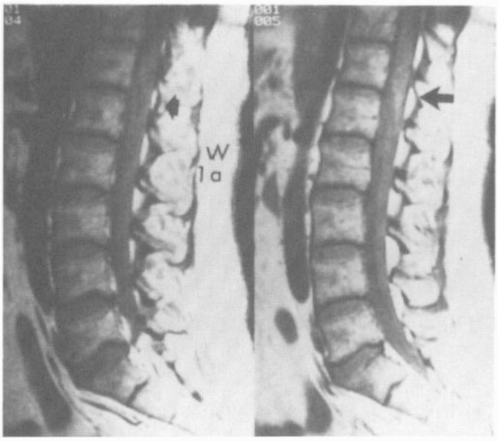
In 3-D FLASH gradient-echo sequences the contrast in T-1 appears to be superior to the one provided by 2-D spin-echo techniques. The improved T-1 contrast of the 3-D FLASH system also increases the enhancing effect of Gd-DTPA.[41]

The present research in the area of 3-D technology is also focused on the possibility of combining in a clinical setting the 3-D brain display with functional data obtained from positron emission tomography scans.[42]

The main region most extensively investigated at present with 3-D techniques is the central nervous system. Our first experiences with the application of this imaging modality in trauma of the spine and spinal cord are promising. The imaging process is faster and the data displayed in the images are more abundant and informative. Both of these qualities are significant when MRI is carried out on a paraplegic or quadriplegic patient, especially soon after the spinal injury. The images presented here, as an example, support this opinion about the 3-D method (Fig 10). However, more time will be needed to evaluate fully the diagnostic advantages of 3-D MRI.[43]



b A 3-D image in the posterior oblique view: the left inferior facet of C4 has jumped anteriorly (arrow) leaving the superior facet of C5 bare (arrow). The widening of the interspinous distance and rotation of the spine at that level are also depicted.



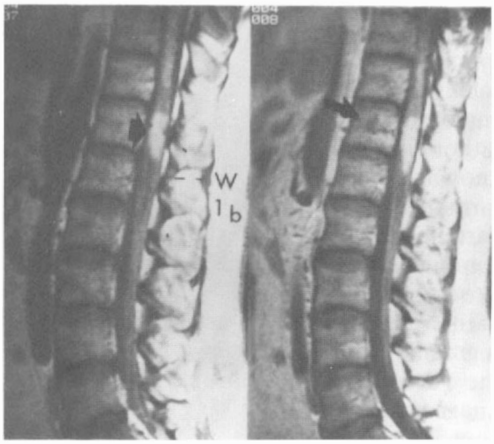


Figure 11a A saggital MR image of a 42 year old male with a severe progressive weakness of the lower extremities, shows a lesion in the area of the conus (arrow).

b Following the application of gadolinium the lesion appears bright (arrow). The diffusion of gadolinium is seen above and below the lesion indicating the possibility of enlarged cord's blood vessels.

c Angiography disclosed an extensive arterio-venous shunt (arrow). At surgery an arterio-venous malformation was found at the level of T12. The patient had a severe injury of the spine in a MVA about two years ago.

MR angiography (MRA)

Spinal cord injuries are commonly associated with more or less severe disturbances of blood flow, often caused by lacerations, thrombosis or embolization of the cord's feeding arteries. In the later phase, arterio-venous shunts or anomalies of the venous system may occur. Thus, it is important for clinical assessment and the planning of treatment to have an accurate knowledge about the magnitude of the damage caused to the spinal cord and its blood supply by trauma to the spine. This may be especially true for some patients in which MRI techniques disclose a minor involvement of the cord substance in contrast to the severity of the clinical signs caused by an obstruction to blood flow.[44] So far, the evaluation of the spinal cord vascular network has been achieved by means of selective spinal cord angiography. However, this procedure is rather complex and there may be some well known complications.[45] Hence, the performance of selective angiography in a paraplegic or quadriplegic patient is at best complicated and it may also aggravate the existing condition.[46]

In MR images one can incidentally see segments of an artery or vein belonging to the vascular system of the spinal cord. In images with enhancement these vessels may appear more prominent if arterio-venous shunt or venous thrombosis are present.[47] But apart from the latter situations, the MRI of the spinal cord blood supply has so far been unsuccessful due to different technical obstacles such as vessel size and tortuosity, the unpredictable nature of the blood flow, and turbulence. Furthermore, the resolution obtained with MR has been 2 to 5 times inferior to that obtained by conventional or digital subtraction selective spinal cord angiography (Fig 11).

Nevertheless, the recently attained improvements of MR angiographic technology have brought this diagnostic modality closer to clinical utility. The new imaging methods tested, including cardiac-gated spin-echo, gradient-echo, out-of-field saturation-pulse sequences, have improved the image quality. Successful tests were also achieved by using 3-D MRA. Moreover, clinically usable data about the state of both carotid arteries were demonstrated in 3-D FLASH sequences. The application of gadolinium compounds have, in addition, further improved the blood flow signal and consequently also the image quality.[48]

The clinical application of MRA for the evaluation of the extra and intracranial blood flow has notably increased in the course of the past year.[49–51] However, our experiences with MRA of spinal cord lesions are rather limited, especially concerning traumatic lesions.[52] As further refinements of MRA technology are expected, its broader use in the evaluation of spinal cord trauma is only a question of time. The properties of MRA are most suitable for the imaging of the spinal blood flow, with or without enhancement, in particular with regard to its safety, the possibility to repeat the study, and the fact that there is little discomfort to the patient.

Conclusion

This brief description of 4 new MR techniques represents a review of some diagnostic modalities that are expected to broaden the clinical application of MR in the evaluation of spinal cord trauma and improve its accuracy. We omitted to elaborate upon the physical properties of the 4 MR advancements because this was not the purpose of our communication. In the references, however, a number of excellent studies dealing with this matter are mentioned.

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