Use of Magnetic Resonance Imaging in Spinal Trauma: Indications, Techniques, and Utility

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Abstract

Magnetic resonance (MR) imaging of acute spinal injury provides excellent visualization of neurologic and soft-tissue structures in a noninvasive format. Advances in imaging-sequence techniques have made possible more rapid acquisition of images with greater spatial resolution. Appropriate selection of imaging sequences allows improved imaging and contrast of the pathologic processes involved in acute spinal trauma, including spinal cord, soft-tissue, and ligamentous injury. Three patterns of spinal cord injury have been identified. Type I is representative of acute cord hemorrhage. Type II represents spinal cord edema. Type III is a mixed hemorrhagic-edematous presentation. Correlation of MR findings with experimental and clinical spinal cord injury has given a relative predictive value to spinal cord injury patterns on MR images indicative of long-term neurologic outcome. Magnetic resonance imaging is useful in delineating soft-tissue injuries associated with spinal column trauma. Despite the improved spatial resolution of MR imaging, plain radiography and computed tomography remain the standard modalities for visualizing spinal fractures.

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The advent of magnetic resonance (MR) imaging has revolutionized the imaging of body tissues and pathologic changes. In its application to spinal trauma, MR imaging provides superior imaging of damaged spinal soft tissues and neural structures, with the advantage over other modalities of being noninvasive. Although primarily useful in visualizing soft-tissue structures, including the spinal cord, improvements in MR imaging technique and resolution have led to an increasing role in the imaging of spinal fractures. However, the disadvantages of MR imaging, including expense, logistics, and the difficulty of imaging the critically injured patient with spinal trauma, necessitate judicious use of MR imaging in the treatment algorithm of the patient with spinal trauma.[1]

Fundamentals of MR Imaging

Magnetic resonance imaging employs a strong stationary magnetic field to initiate parallel alignment of the hydrogen proton dipole moments within a studied tissue.[2,3] The application of an external radiofrequency (RF) pulse results in energy absorption by the hydrogen protons in the tissue, with resultant changes in dipole direction and precession (i.e., dipole moment rotation). Dipole moment directional and precessional changes are dependent on the direction of the applied RF pulse with respect to the alignment of the stationary magnetic field, B_0. After cessation of the RF pulse, the energized precessional coherence of the proton dipoles dissipates—that is, the protons "relax" to a more stable, unsynchronized energy state. This release of absorbed energy occurs as an RF wave with a time-dependent decay and is recorded and spatially encoded by a computer to produce an electronic image.

During relaxation, dipole moment realignment within the stationary magnetic field, B_0, depends on the thermal-energy dissipation characteristics of the surrounding environment, or molecular lattice; this spin-lattice, or T1, relaxation time represents an increasing return of the net dipole magnetic vector alignment on the z-axis parallel to B_0. Dipole precessional desynchro-

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nization, or dephasing, depends on the ability of the excited protons to dissipate energy by inducing spin in adjacent unexcited molecules; this spin-spin, or T2, relaxation time represents a decreasing magnetic vector on the x,y-plane perpendicular to B_0. The T1 and T2 relaxation times occur simultaneously and independently of each other and form the basis of tissue contrast in MR-reconstructed images.

Spinal-Tissue Relaxation Characteristics

Protons within large molecular complexes, such as proteins and lipids, tend to dissipate thermal (spin-lattice) energy more efficiently than protons in small molecules, such as those of water and cerebrospinal fluid (CSF). Over a given period of T1 relaxation signal measurement, lipids and proteins will demonstrate a greater gain of signal intensity (i.e., will appear whiter) on the z-axis than tissues with high water content.

Similarly, protons within large molecular complexes, such as proteins and lipids, tend to dissipate energy by spin induction in unexcited protons, or spin-spin interactions, more efficiently than smaller molecules, such as those of water. Over a given period of T2 relaxation signal measurement, lipids and proteins will demonstrate a greater loss of signal intensity (i.e., will appear darker) on the x,y-plane than tissues with high water content. Tissues with high type I collagen content (e.g., ligaments) will also exhibit decreased T2 signal due to the restriction of water movement in such a highly organized molecular structure with enhanced dipole-dipole interactions.

Pulse-Sequence Parameters

The selection of RF pulse-sequence parameters affects the contrast of reconstructed images and can be used to enhance the definition of the anatomic and pathologic features of spinal tissue. In general, the three pulse sequence parameters that are modified to produce tissue contrast are the repetition time (TR), the echo time (TE), and the flip angle.[2-4]

The pulse TR is the interval between the RF pulses used to energize protons within the stationary magnetic field. The T1 contrast depends inversely on the TR. Long TRs allow complete dipole relaxation between pulses and reduce the contrast between tissues of differing T1.

Periodically rephasing RF pulses in the x,y-plane, termed the "echo train," are employed within the TR interval to enhance the RF signal released from dipole dephasing. The TE is the time period between the initial RF excitation pulse and the collection of the recovered echo signal by the imaging coil. The T2 contrast depends primarily on the TE. A longer TE allows a longer period of signal acquisition and increases the contrast between tissues of differing T2, but at the cost of a diminished signal-to-noise ratio due to increasing signal decay with each TE collection period.

"Flip angle" refers to the angular displacement of the dipole moment by the applied RF excitation pulse. The TR interval pulses vary from 10 degrees to 90 degrees with respect to the z-axis of the stationary magnetic field, B_0. The TE interval refocusing pulses are at 180 degrees within the x,y-plane of B_0.

Pulse-Sequence Selection

Variation of pulse-signal parameters within the MR imaging signal sequence can be used to affect the image contrast, resolution, and acquisition time. In conventional spin-echo (SE) technique, the pulse sequence consists of a 90-degree RF pulse followed by a series of 180-degree rephasing pulses. T1-weighted, T2-weighted, and proton-density-weighted images are produced by varying the TR and TE while the flip angle remains constant at 90 degrees.

For SE T1-weighted images, the TR and TE are short (300 to 700 and 20 to 40 msec, respectively). On conventional SE sequences, anatomic detail is clearest on T1-weighted images. Adipose tissue, bone marrow, and protein-rich fluids are depicted as high signal intensity (i.e., as mentioned previously, they appear whiter), and water and CSF are depicted as low signal intensity (i.e., they appear darker).

For T2-weighted images, the TR and TE are long (2,000 to 3,000 and 70 to 100 msec, respectively). Water and CSF exhibit higher signal intensity than soft-tissue and osseous structures. T2-weighted images emphasize pathologic changes because many such processes (e.g., tissue edema and acute hemorrhage) are characterized by an abnormally high water content. The addition of a frequency-selective fat-suppression technique in spinal trauma cases significantly increases the conspicuity of marrow edema and, hence, that of radiographically occult fracture. Use of a fat-suppression technique also increases the contrast between normal and edematous soft tissue, facilitating the detection of paravertebral and ligamentous trauma.

With proton-density-weighted imaging, a balance is achieved between T1- and T2-weighting. This sequence is useful in delineating ligamentous anatomy. A long TR is selected to deemphasize T1 weighting, and a short TE is selected to deemphasize T2 weighting. A typical pulse-sequence selection would have a TR of 2,000 to 3,000 msec and a TE of 20 msec. The CSF and spinal cord appear isointense (gray) on proton-density-weighted images. Ligamentous structures may be more clearly defined due to their lower signal intensity on both long-TR and short-TE images.

Use of conventional SE sequences allows a thorough evaluation of the spine with comparative tissue contrast provided by T1-, T2-, and proton-density-weighted images (Table 1). Disadvantages include prolonged acquisition times with motion-artifact susceptibility, particularly for T2-weighted images, and a decreased signal-to-noise ratio with poor resolution for T2-weighted images (Table 2).

In an effort to minimize T2 imaging times, a gradient-echo (GRE) pulse sequence is often used. With GRE imaging, a smaller flip angle, typically 10 to 30 degrees, is used in combination with short TR and TE to reduce total imaging time. Additional time is saved by substituting a quickly reversible electrical gradient for the conventional 180-degree refocusing pulses. Like T2-weighted images, GRE images produce a “myelogram effect” image due to the high signal intensity of CSF. Gradient-echo imaging is particularly sensitive in the detection of hemorrhage due to a lack of correction for field inhomogeneities, such as those that result from the paramagnetic effects of hemoglobin degeneration products. Disadvantages of GRE imaging include poor delineation of herniated disk material, exaggeration of spinal canal stenosis (“blooming”), and minimization of cord size.

Recent technique developments allow fast-spin-echo (FSE) sequencing, whereby additional refocusing sequences are incorporated with a given TR interval.[5] Advantages include faster image-acquisition times and a subsequent decrease in motion artifact. The addition of multiple refocusing sequences allows an increased matrix size, hence improved spatial resolution, and the greater correction for field inhomogeneity inherent with dipole dephasing. The disadvantages of this technique include a decreased sensitivity to paramagnetic effects, including those due to the by-products of occult hemorrhage.

Table 1
Tissue Characteristics on MR Imaging*

Tissue	Imaging Sequence T1	T2	PD	GRE
Fat	++	+	+	+
Bone, cancellous	+/++	+	+	+
Bone, cortical	−	−	−	−
Intervertebral disk (normal)	−	++	+	++
Ligaments	−	−	−	−
Spinal cord	+	+/−	+	+/−
Cerebrospinal fluid	−	++	+	++

* Abbreviations and symbols: GRE = gradient-echo; PD = proton-density-weighted; ++ = high (white) signal; + = isointense (gray) signal; − = low (black) signal

MR Imaging Characteristics of Spinal Trauma

Imaging of the acutely injured spine is best accomplished with a high-field-strength system, preferably 1.5 teslas (T). While the signal-to-noise ratio is maximized in a high-field-strength system, useful diagnostic information regarding both the cord and the spinal canal can be obtained at medium or low strength (0.5 T).[6] Disadvantages of low-field-strength systems include the longer imaging time and the prolonged time that an acutely traumatized patient must remain stationary in the MR unit. Al-

Table 2
Advantages and Disadvantages of Pulse-Signal Sequences

Pulse Sequence	Advantages	Disadvantages
Conventional spin-echo	Imaging standard	Long T2 imaging times Low T2 signal-to-noise ratio Susceptible to motion artifact
Gradient-echo	Fast imaging time “T2 like” image Hemorrhage-sensitive Reduced motion artifact	Poor disk delineation Exaggerates canal stenosis Minimizes spinal cord size Poor contrast between fat and muscle
Fast-spin-echo	Faster imaging times with improved resolution Reduced motion artifact Decreased signal inhomogeneity	Bright fat signal on T2 Reduction in signal loss with hemorrhage

though the cervical and the thoracic spines are best imaged at a high field strength, the advent of new software and hardware upgrades have markedly improved image quality on low-field-strength and open systems.

Image resolution is enhanced by the use of surface coils and motion-compensating gradients for the suppression of CSF flow artifacts.[4] Appropriate selection of pulse sequences will maximize visualization of spinal trauma and minimize imaging times in the critically injured patient with spinal trauma. Our recommended MR imaging sequences for spinal trauma are FSE with all images obtained on a phase-array spine coil (Table 3).

Table 3
Recommended MR Imaging Sequences for Spinal Trauma*

Level and Type of Image	Matrix	Field of View, cm	Section Thickness, mm/Skip	Peripheral Gating
Cervical				
Sagittal	512 × 256	22 × 16	3.5/0	No
Axial	256 × 192	15 × 15	2.5/0	Yes
Thoracic				
Sagittal and axial	512 × 256	34 × 25	4.0/1	Yes
Lumbar				
Sagittal	512 × 256	28 × 28	4.0/1	No
Axial	512 × 256	18 × 18	4.0/1	No

*All images are FSE technique obtained with a phase-arrayed spine coil.

Edema and Hemorrhage

Trauma to spinal tissues typically results in edema or hemorrhage. The increase in tissue water makes these injuries particularly amenable to diagnosis by MR imaging. Injury-based edema within soft tissues, ligaments, and spinal parenchyma is best visualized on T2-weighted or GRE images as an increased signal intensity compared with adjacent normal tissues. Due to the paramagnetic characteristics of hemoglobin iron, hemorrhage visualization on MR imaging is dependent on hematoma age and tissue location.

Five distinct MR imaging stages of hemorrhage within brain and spinal cord parenchyma[7] (Table 4) have been identified: (1) Hyperacute hemorrhage (age, less than a few hours) contains intracellular oxyhemoglobin, which is visualized as low signal intensity on T1-weighted images and high signal intensity on T2-weighted images. (2) Acute hemorrhage (age, 1 to 3 days) contains intracellular deoxyhemoglobin and is visualized as low signal intensity on T1- and (particularly) T2-weighted images. (3) Early subacute hemorrhage (age, 3 to 7 days) contains intracellular methemoglobin and is visualized as high signal intensity on T1-weighted images and low signal intensity on T2-weighted images. (4) Late subacute hemorrhage (age, more than 7 days) contains extracellular methemoglobin and is visualized as high signal intensity on T1- and T2-weighted images. (5) Chronic hemorrhage (age, more than 2 weeks) is primarily ferritin and hemosiderin and is visualized as low signal intensity on T2-weighted images. In contrast, hematoma formation within the soft tissues, intervertebral disks, or epidural space is primarily methemoglobin by the subacute stage and is visualized as high signal intensity on T2-weighted images.[7]

Spinal Cord Injury

Perhaps the most important application of MR imaging in spinal trauma is the noninvasive visualization of the spinal cord. In a series of 27 patients with acute spinal cord injuries imaged with conventional sequences, Kulkarni et al[8] identified three patterns of injury within the spinal cord. Pattern I (Fig. 1) was notable for a large area of low sig-

Table 4
Hematoma Characteristics on MR Imaging*

		Signal Intensity	
Stage of Hematoma	Age	T1	T2
Hyperacute	<6 hr	Low	High
Acute	1-3 days	Low	Low
Early subacute	3-7 days	High	Low
Late subacute	>7 days	High	High
Chronic	>2 weeks	Isointense	Low

*Appearance on conventional SE series.

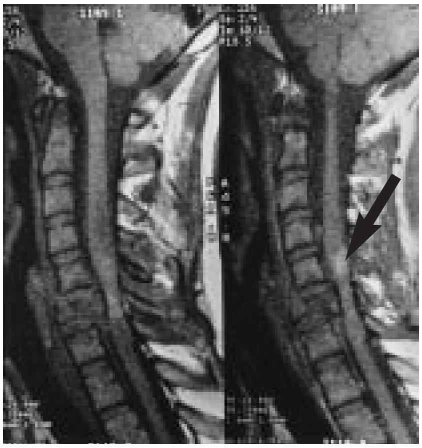


Fig. 1 Pattern I injury. Burst fracture of C6 in a 22-year-old man imaged 1 week after injury. Sagittal T1-weighted image demonstrates retropulsion of bone into the cervical canal compromising the spinal cord. Signal hyperintensity within the cervical cord (arrow) indicates a hemorrhagic cord contusion. The patient demonstrated no clinically apparent neurologic recovery.

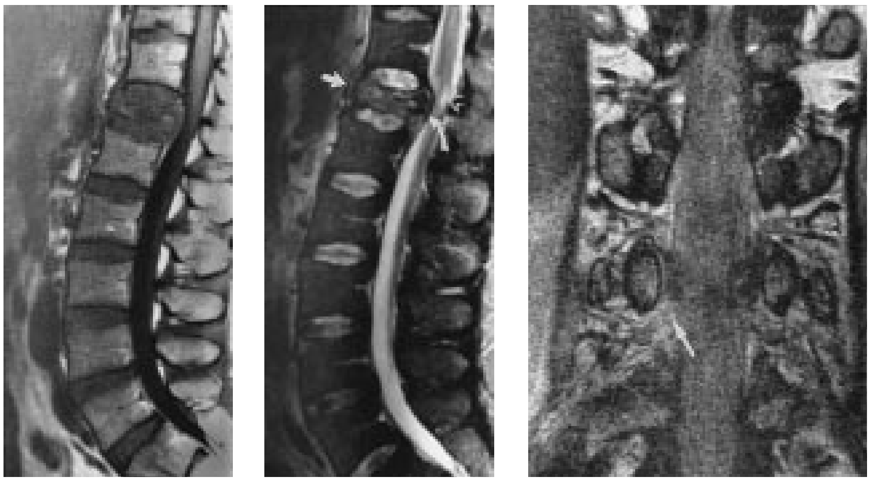
nal intensity on T2-weighted images and was attributed to acute hemorrhage within the spinal cord. In later subacute phases, peripheral hyperintensity was noted on T1-weighted images. Cord transection was inferred from the presence of a gap between cord signal segments or a complete loss of spinal cord signal at the injury site on early T1-weighted images. Pattern II (Fig. 2) demonstrated a large area of high signal intensity on T2-weighted images and was considered to represent cord edema. Pattern III (Fig. 3) was mixed, with a small area of low signal intensity surrounded by a thick rim of high signal intensity on T2-weighted images. This was interpreted as a small central hemorrhage surrounded by edema. In experimental spinal-cord-injury models, Hackney et al[9] and others[10] confirmed that MR imaging findings correlated with the histopathologic findings of acute spinal cord injury in the described time-dependent manner.

Soft-Tissue Injury

Magnetic resonance imaging has proved highly sensitive to spinal-column soft-tissue injury, particularly ligament disruption, disk herniation, and dural disruption. Typical findings include increased signal intensity on T2-weighted images in structures of characteristic low signal intensity, most notably those of high type I collagen content.

Ligamentous injury, which previously could only be inferred, can be demonstrated clearly by MR imaging.[11] Determination of posterior spinal ligament integrity may be important to the assessment of stability in the traumatically injured spine.[12] Preoperative MR imaging can assist the surgeon if the assessment of ligamentous disruption is a critical factor in determining the type of treatment. Emery et al[13] reported that MR imaging detected ligament damage in 17 of 19 trauma patients considered to have torn posterior ligaments on the basis of surgical, clinical, and/or radiographic findings.

Spinal ligament injury is best seen on FSE sequences as increased matrix size and improved spatial resolution (Fig. 4). An intact supraspinous ligament and an intact pos-



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D

Fig. 2 Pattern II injury. Burst fracture of T12 in a 37-year-old man with bladder dysfunction. Images were obtained 3 days after injury. **A,** Sagittal FSE T1-weighted image demonstrates burst fracture with bone retropulsion into the canal. **B,** Sagittal FSE T2-weighted image depicts marrow edema within the T12 vertebral body. Note deformity of the anterior longitudinal ligament (straight arrow) and posterior longitudinal ligament (curved arrow). Edema without hemorrhage is evident in the conus (open arrow). **C,** Coronal FSE T2-weighted image through the thecal sac demonstrates hyperintensity in the proximal right T12 root (arrow), indicating a contusional injury. **D,** Axial FSE T2-weighted image depicts 50% canal compromise due to retropulsed bone (arrows).

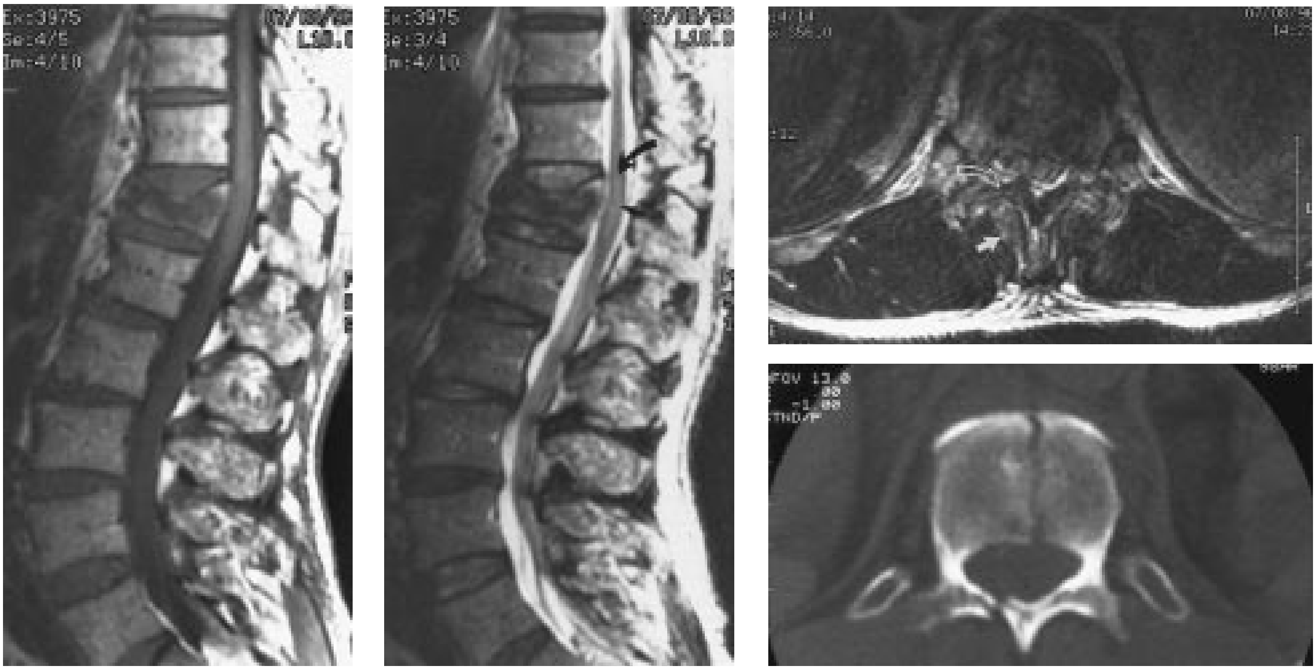

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Fig. 3 Pattern III injury. Burst fracture of T12 in a 66-year-old man with right footdrop imaged 4 days after injury and transfer to a trauma institution. **A,** Sagittal FSE T1-weighted image demonstrates marrow edema within the T12 vertebral body and swelling of the conus. **B,** Sagittal FSE T2-weighted image depicts edema (curved arrow) with punctate hemorrhage (straight arrow) in the conus. **C,** Axial FSE T2-weighted image **(top)** demonstrates canal compromise, right laminar cortex irregularity (curved arrow), and increased signal intensity in adjacent soft tissues (straight arrow), suggestive of concurrent posterior laminar fracture. Pronounced motion artifact is present; a repeat study would be recommended. Corresponding CT scan of T12 **(bottom)** depicts vertebral body and right laminar fracture.

terior longitudinal ligament appear as thick black strips on both T1- and T2-weighted sagittal images. Ligament injury is represented by increased signal intensity within the ligament substance or by discontinuity of ligament signal suggestive of complete rupture.[11,13] In patients with ankylosing spondylitis and diffuse idiopathic skeletal hyperostosis, ligamentous disruption may be the most important feature in assessment of spinal stability after thoracic spinal fracture.

Posttraumatic disk herniation can present as either high or low signal intensity on FSE T2-weighted or GRE images, depending on the presence of intradiskal hemorrhage: decreased intradiskal signal intensity and loss of disk height are seen in cases of disk rupture without

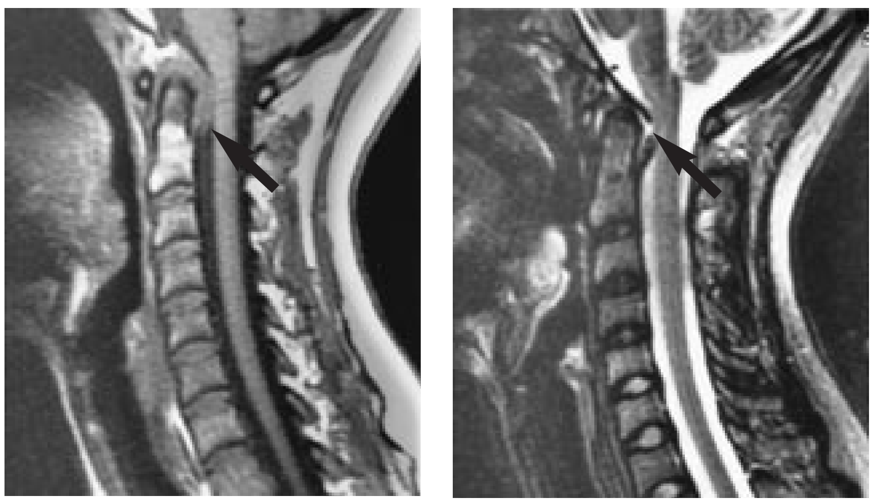

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Fig. 4 Isolated ligamentous trauma in a 35-year-old woman imaged 2 weeks after a cervical flexion injury. **A,** Sagittal FSE T1-weighted image demonstrates intermediate signal intensity (arrow) posterior to the odontoid. Due to the limited soft-tissue contrast of the sequence, the transverse ligament is not well visualized. **B,** Sagittal FSE T2-weighted image depicts to better advantage a traumatic tear of the transverse ligament and posterior longitudinal ligament (arrow).

hematoma; increased intradiskal signal intensity is seen in cases of traumatic disk rupture with hematoma formation. On T1-weighted images, traumatic disk herniation typically appears isointense or decreased in signal intensity (Fig. 5).

The combination of clinical findings and MR evidence of occult cervical disk herniation is useful in guiding the selection of surgical approach for patients with facet injuries. In one large series, Flanders et al[14] reported a 50% incidence of posttraumatic disk herniation in spinal-cord-injured patients with cervical involvement. Eismont et al[15] noted an 11% incidence of increased neurologic compromise during reduction of facet dislocations under anesthesia, which was attributed to unrecognized disk herniation. Thus, MR imaging of the disk is crucial for patients undergoing reduction of a facet dislocation under general anesthesia.

Dural damage, such as nerve-root avulsion, is most notable for high signal intensity within the epidural space or neural foramen on T2-weighted or GRE images, which is secondary to pseudomeningocele formation (Fig. 6). Displacement of the spinal cord by the pseudomeningocele is best evaluated on axial sections. The T2-weighted characteristics of a pseudomeningocele may be slightly different from those of the surrounding CSF, typically due to an admixture of hemorrhagic or proteinaceous debris. Nerve-root contusional injury, as occurs with intramedullary spinal cord damage, is depicted as increased signal intensity within the nerve-root parenchyma on T2-weighted or GRE images (Fig. 2, C).

In cases of acute spinal trauma, epidural fluid collections may also represent hematoma. In contrast to soft-tissue hemorrhage patterns, hematoma in the epidural space is primarily methemoglobin by the subacute stage and is visualized as high signal intensity on T1- and T2-weighted images (Fig. 7). Spinal trauma in patients with ankylosing spondylitis is notable for epidural hematoma formation.[16]

Because of its superior soft-tissue visualization and its noninvasive nature, MR imaging is increasingly replacing the combination of computed tomography (CT) and myelography in the assessment of spinal canal trauma. In certain cases of suspected nerve-root avulsion, CT-myelography remains useful in delineating the formation of pseudomeningoceles; however, such defects may elude detection due to contrast obstruction by injury hematoma or edema, which would not occur with MR imaging. In the diagnosis of spinal trauma, CT-myelography remains a diagnostic option when MR imaging is not available or is contraindicated.

Fractures

Improved sequencing techniques have led to the increased sensitivity of MR imaging to spinal fracture. Compressive fractures within cancellous bone are evidenced by decreased signal intensity of marrow on T1-weighted images and increased signal intensity

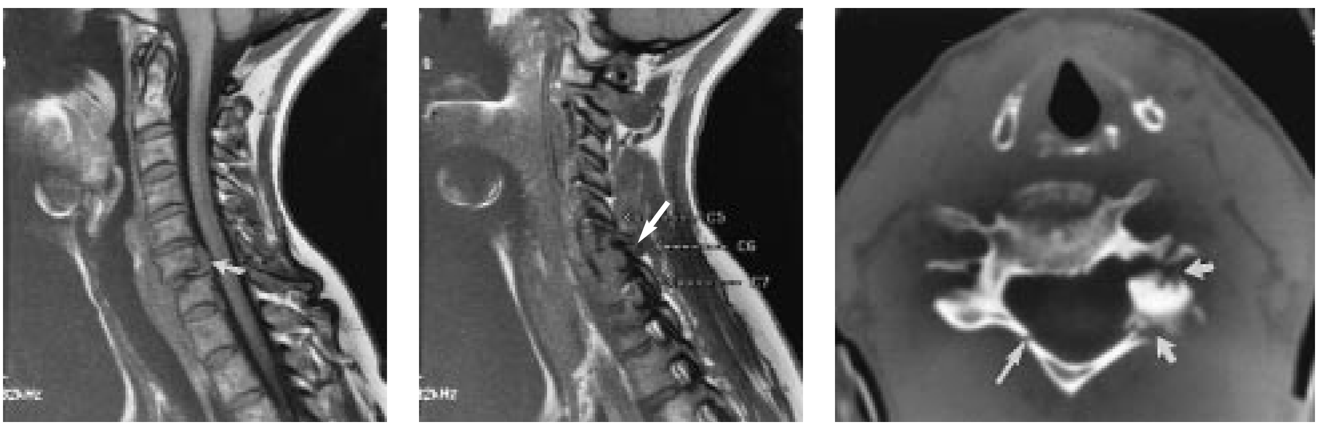

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Fig. 5 A lateral mass fracture in a 49-year-old woman. **A,** Sagittal FSE T1-weighted image demonstrates anterior translation of C6 on C7 with an extruded disk migrating cephalad behind the C6 vertebral body (arrow). **B,** Left paramedian FSE sequence illustrates subluxation of the left C6-7 facet joint. Note the displaced bone fragment (solid arrow) due to the disruption of the inferior articulating C6 facet. **C,** Corresponding CT image depicts a left fracture separation of the lateral mass (short arrows) as well as a minimally displaced right laminar fracture (long arrow).

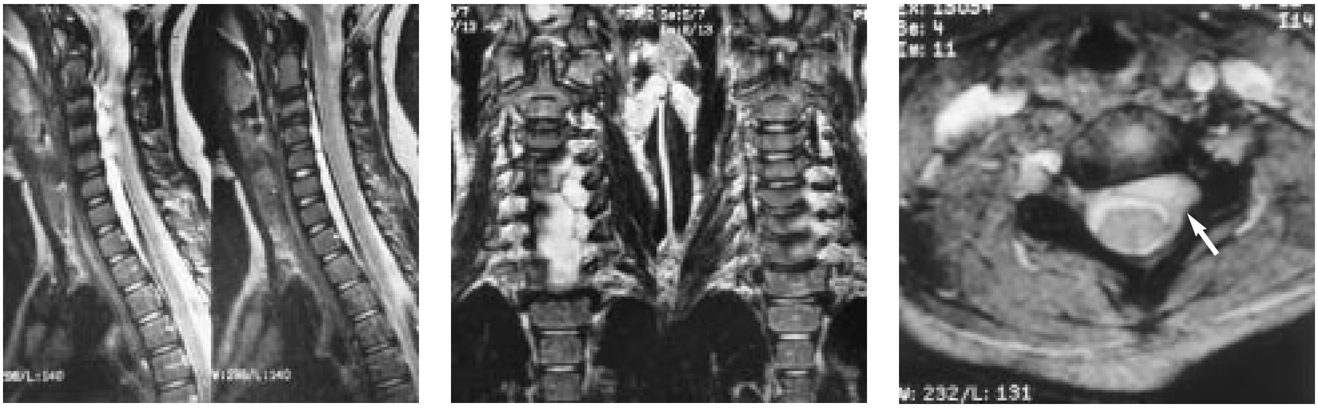

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Fig. 6 Traumatic cervical root avulsion and pseudomeningocele in a 6-year-old girl. **A,** Sagittal FSE T2-weighted images depict a large fluid collection that compresses the ventral portion of the thecal sac and obscures the normally high-intensity signal of the CSF adjacent to the cord. The fluid collection represents a large pseudomeningocele. **B,** Coronal FSE T2-weighted images demonstrate to better advantage the extent of the root injury with pseudomeningoceles arising from the left C5, C6, C7, and C8 levels. **C,** Axial GRE image illustrates displacement of the cervical cord and thecal sac to the right of midline by a large left-sided pseudomeningocele (arrow) at the C5-6 level.

on T2-weighted and GRE images (Figs. 1-3). The use of frequency-selective fat suppression increases the conspicuity of marrow edema on T2-weighted and GRE images. Improved spatial resolution and decreased signal-to-noise ratios on FSE imaging have led to improved delineation of cortical fractures in the sagittal plane (Fig. 5). The excellent anatomic detail inherent with T1-weighted imaging and the ability to discern ligamentous injury have made MR imaging particularly useful in assessing injury to the atlanto-occipital and cervicothoracic regions.[7,17] Axial imaging of cortical fractures is less clear due to signal-to-noise issues; such fractures are best detailed on T2-weighted images obtained with the addition of fat-suppression techniques (Figs. 2, D; 3, C).

Vascular Injury

The noninvasive nature of MR angiography has led to its increasing role in the screening of cervical spine trauma. Friedman et al[18] reported abnormal findings on MR angiograms of 9 (24%) of 37 cervical trauma patients. In that study, routine SE and GRE sequences were supplemented by two-dimensional time-of-flight MR imaging. Arterial injury was present in 50% of patients with complete motor and sensory lesions, compared with 12% of patients with incomplete injuries.

Magnetic resonance angiography appears to be sensitive in the diagnosis of vessel occlusion; however, it is not as sensitive as conventional angiography in the detection of vertebral artery dissection. Despite an increased radiographic prevalence, the clinical frequency of vertebrobasilar ischemia in patients with cervical spine trauma is low, and the treatment remains controversial in the presence of concurrent spinal cord injury.[18] The results of such injuries in symptomatic patients can be neurologically devastating. In general, MR angiography is indicated for patients with concurrent spinal trauma and brain injury and for patients with rapid central neurologic deterioration following acute cervical spine trauma.[18]

Comparison of CT and MR Imaging

Despite the improvements in cortical bone resolution with MR imaging, plain radiography and CT remain the standard modalities for delineation of cortical fracture patterns. Levitt and Flanders[19] compared the CT and MR imaging findings in a series of 49 patients with acute cervical spinal column injury and reported the sensitivity of MR imaging in detecting osseous injury as 46%; specificity, 100%; positive predictive value, 100%; and negative predictive value, 48%. Flanders et al[14] reported an MR imaging sensitivity for vertebral fractures of 71%, with a 93% specificity when concurrent CT was used as the standard of reference. Cervical posterior-element fractures were less well visualized on MR imaging, with a reported 25% sensitivity and 100% specificity as compared with CT.

Difficulties in imaging cortical fractures, particularly of posterior elements, are due to their inherent low water content and the fact that

Fig. 7 Type II odontoid fracture in 21-year-old man with progressive neurologic deterioration and quadriplegia. **A,** Sagittal FSE T1-weighted image demonstrates proximal paravertebral edema and diffuse cord enlargement. **B,** Sagittal FSE T2-weighted image depicts paravertebral edema and signal hyperintensity within the cord, consistent with edema and hemorrhage. A fluid collection of high signal intensity that differs from adjacent CSF at the distal ventral epidural space is suggestive of an epidural hematoma. Use of GRE imaging would better confirm the suspicion of epidural hematoma. **C,** Sagittal proton-density image shows intermediate signal intensity posterior to the odontoid and a traumatic tear of the posterior longitudinal ligament (arrow). **D,** Axial FSE proton-density (left) and T2-weighted (right) images delineate ventral epidural hematoma. **E,** Sagittal CT reconstruction delineates a fracture through the base of the odontoid with anterior displacement.

MR depicts cortical bone as a signal void rather than as a positive signal. However, vertebral body cancellous fractures are well visualized due to postinjury marrow edema and hemorrhage in contrast to surrounding marrow elements.

MR Imaging as a Prognostic Tool in Spinal Trauma

As previously stated, the value of MR imaging has been in its visualization of intramedullary spinal cord injury. Experimental studies have shown a close correlation of MR imaging findings with the temporal histopathologic findings of primary[9] and secondary[10] spinal cord injury. The correlation of MR findings with histologic patterns supports the prognostic usefulness of MR imaging in predicting the long-term level of neurologic deficit.

In their initial description of cord injury patterns on MR images obtained within 10 days of injury, Kulkarni et al[8] reported a consistent relationship between the described injury patterns and the patient's Frankel grade at the time of discharge. Patients with type I injuries, characterized by large intramedullary hemorrhage, typically presented with a complete cord syndrome (Frankel grade A) and showed no recovery. In type II injuries, characterized by intramedullary edema, patients demonstrated incomplete cord syndromes with subsequent improvement of at least one Frankel grade. Patients with type III mixed hemorrhagic-edematous lesions had less initial neurologic impairment and improved during their hospital course.

In a serial MR imaging study of acute spinal cord injury with 1-year follow-up, Bondurant et al[20] reported similar results with the use of both the Frankel grade and the motor index score. At an average of 12.1 months after injury, patients with type I injury patterns showed no improvement in Frankel classification and only minimal improvement in motor index score (from 32.1 to 42.4 on a 100-point scale). In contrast, all patients with type II and type III injury patterns improved at least one Frankel grade. The mean motor index score for type II patients increased from 70.8 to 91.9; that for type III patients, from 37.3 to 75.7.

In general, type I injuries are characterized by severe cord parenchymal injury, resulting in physiologic, if not anatomic, cord transection. The prognosis for functional recovery is poor. Type II injuries appear primarily edematous and carry a good prognosis for functional recovery. Type III injuries are mixed hemorrhagic-edematous lesions and carry a compromised, though favorable, prognosis for some functional recovery.

Indications for MR Imaging in Spinal Trauma

An algorithm for the use of MR imaging in spinal trauma, based on an understanding of MR utility and findings, is presented in Figure 8. In general, MR imaging should be ordered only in those cases in which plain radiographs and CT scans do not provide enough information for the surgeon to proceed with effective treatment. The diagnostic strength of MR imaging lies in its usefulness in assessing neurologic and soft-tissue structures.

Magnetic resonance imaging may be indicated after routine radiography and CT for patients with evidence of acute fracture and an incomplete neurologic deficit.[2-4,8] In this scenario, MR imaging provides the surgeon with information regarding the character of the spinal cord injury and a basis for neurologic prognosis, in addition to identifying any associated ligamentous injury that could affect the selection of an operative approach for stabilization. Theoretically, the greatest prognostic value of MR imaging would be at the point of maximal spinal parenchymal necrosis, which typically occurs 5 days after injury[9,10]; however, practical treatment often necessitates earlier imaging. In preoperative planning, CT will best delineate the spinal fracture pattern.

Magnetic resonance imaging is generally not indicated in cases of complete neurologic deficit, as the results are unlikely to affect patient treatment or outcome. In such cases, CT is more effective in determining the operative treatment plan. A possible exception is the patient with a cervical facet dislocation who is undergoing reduction under anesthesia; failure to identify an occult disk herniation before reduction may result in loss of neurologic function.

Magnetic resonance imaging is indicated in the evaluation of patients who have a neurologic deficit but whose radiographs do not show fracture (commonly described with the phrase "spinal cord injury without radiographic abnormalities," or SCIWORA). Typical presentations are in pediatric patients with traumatic spinal ligament hypermobility and in older patients with central cord syndrome secondary to a hyperextension event in the presence of cervical canal stenosis.[1] Magnetic resonance imaging will allow characterization of the spinal cord injury, clarify the prognosis, and identify sources of occult cord compression.[21] In addition, MR imaging is indicated when the level of neurologic injury does not correlate with the level of fracture observed on plain radiographs.

Magnetic resonance imaging of the acutely injured spine should be considered for any patient with a fracture or fracture-dislocation involving the spinal canal or any injury resulting in discontinuity of the longitudinal axis of the canal.[4,11] Magnetic resonance imaging is particularly useful in visualization of sagittal translations at the occipitoatloid or cervicothoracic junctions, which are poorly visualized on plain radiographs; it is also useful when a history of prior neck injury calls into question the acuteness of sagittal subluxation depicted on plain radiographs.[11]

Magnetic resonance imaging should be considered in assessing posterior-column ligament integrity when flexion-extension radiographs are suggestive of instability or when certain fracture patterns, such as thoracolumbar vertebral burst fractures and flexion-distraction injuries, are noted.[13] However, in

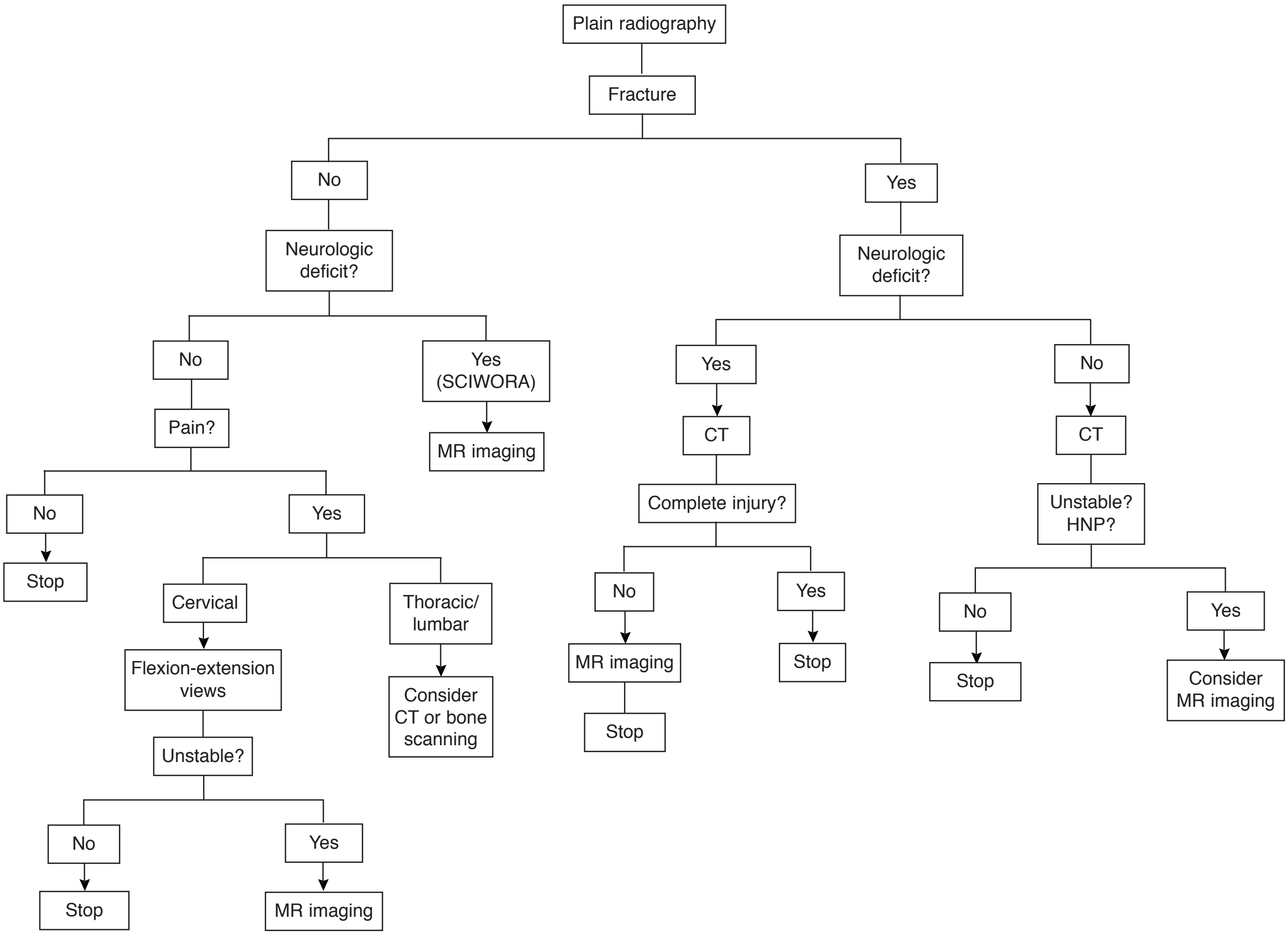

Fig. 8 Diagnostic algorithm for acute spinal trauma. HNP = herniated nucleus pulposus; SCIWORA = spinal cord injury without radiographic abnormalities.

cases of cervical facet dislocation, controversy persists regarding the role of prereduction MR imaging in identifying the source of occult spinal cord compression (e.g., disk herniation or epidural hematoma), which would contraindicate a closed reduction attempt.[15]

Limitations of MR Imaging

Although MR imaging offers superior neural and soft-tissue visualization, a number of limitations must be considered when evaluating the patient with an acute spinal cord injury.[1] Due to the inherent inductance of the stationary magnetic field, electrical shielding of cardiac monitoring devices and use of nonferrous traction devices is necessary. Cranial-tong traction requires the use of water or sand weights so as to avoid inadvertent weight motion in the magnetic field. Coughing by spinal-cord-injured patients with respiratory compromise results in poor image resolution due to motion artifact. Noncompliance is also a problem in patients with severe claustrophobia. Delays in obtaining MR images in many centers may result in delay of appropriate treatment, especially in the polytraumatized patient with spinal injury.

Magnetic resonance imaging is contraindicated for patients who have a pacemaker or aneurysm clips in place. The presence of metallic fragments in the posterior chamber of the eye or near vital neurologic or vascular structures (e.g., retained gunshot fragments) is also a contraindication.[22]

Summary

Magnetic resonance imaging of acute spinal injury provides excellent visualization of neurologic and soft-tissue structures in a noninvasive format. A fundamental understanding of MR sequence parameters and appropriate selection of imaging sequences allows improved visualization of the pathologic processes involved in acute spinal trauma. A collaborative effort between the trauma team and the radiologist is crucial in rendering an expeditious diagnosis of spinal trauma, thereby providing optimal care to the acutely traumatized patient.

Correlation of MR imaging findings with experimental and clinical spinal cord injury has given a predictive value to MR spinal cord injury patterns in terms of long-term neurologic outcome. Despite the improved spatial resolution of MR imaging, plain radiography and CT remain the standard modalities for visualizing spinal fractures.

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