

Medical Imaging of Intervertebral Disc Degeneration

Current Status of Imaging

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Study Design. The author reviewed literature and reports on spine imaging, selected key articles in which novel imaging strategies were described, and prepared a review of currently developing imaging strategies in intervertebral disc degeneration.

Objectives. To provide a review of imaging in intervertebral disc degeneration that covers the current methodology briefly and describes developing techniques in detail.

Summary of Background Data. Computed tomography and magnetic resonance imaging provide excellent anatomic images of the spine. However, anatomic imaging of the spine does not reliably identify the source of pain in patients with intervertebral disc degeneration. Many functional imaging techniques are suited to the study of the spine. Some of these techniques will improve our understanding of intervertebral disc degeneration and clinical symptomatology.

Methods. The author selected reports in the current literature for further review and attempted to describe succinctly the material in the reports that are most relevant to spine imaging.

Results. New and potentially useful imaging strategies for spine imaging include dynamic computed tomography, dynamic magnetic resonance imaging, functional magnetic resonance imaging, diffusion imaging, and magnetic resonance spectroscopy.

Conclusions. Technological advances in magnetic resonance imaging and computed tomography imaging continue to offer more opportunities to investigate and diagnose back pain and intervertebral disc degeneration.

Key words: intervertebral disc degeneration, MRI, MRS, fMRI, CT, diffusion imaging, dynamic CT, dynamic MR. *Spine* 2004;29:2751-2756

Before the development of noninvasive imaging techniques such as computed tomography (CT) and magnetic resonance imaging (MRI), myelography, epidural venography, and epidurography were performed in selected patients with back pain mainly for the purpose of selecting patients for surgical decompression of a nerve root. As CT and MRI have replaced the older techniques, the focus has slowly changed from nerve root compression

as a cause of back pain to other mechanisms. With the contrast and spatial resolution of CT and MR, the detection of disc herniation and nerve root compression has become nearly perfect. Despite its faithful depiction of disc morphology, MR and CT fail to distinguish findings that are symptomatic from those that are incidental. Therefore, in patients without obvious nerve root compression, imaging may fail to demonstrate the cause of pain. The demonstration of disc degeneration does not indicate that it is the cause of back pain. Numerous studies have demonstrated the poor specificity of MR in the diagnosis of patients with back pain.¹ To improve the value of medical imaging in back pain, new imaging strategies are required.

Several MR-based techniques now available provide functional information that may be useful in patients with back pain. With MR, the Brownian movement of water molecules can be tracked and measured. Because tissue structure determines the direction and magnitude of water diffusion, diffusion imaging may be used to examine the structure of spinal tissues. Diffusion-weighted imaging and its more sophisticated form, diffusion tensor imaging (DTI), can be applied to the study of the spinal cord or intervertebral disc. Another MR technique, MR spectroscopy (MRS), can be used to measure the concentration of some tissue metabolites. For example, lactic acid and other metabolites can be measured in the spinal cord or intervertebral disc noninvasively. Magnetic resonance imaging after the injection of intravenous contrast medium provides another functional imaging technique. Measuring the rate at which contrast medium diffuses into the disc provides some measure of the disc's glycosaminoglycan structure. Also, contrast medium can be used to identify nerve roots that have a deficient blood-nerve barrier. With neurography, a high resolution MR technique, functional changes in spinal nerve roots and peripheral nerves can be evaluated. With functional MRI (fMRI), the neuronal function within the spinal cord can be studied. Finally, and most importantly, with dynamic CT or MR imaging of the spine, the motions of the spine can be studied noninvasively and the "stability" of the spine probed as it is subjected to a load or torque. Dynamic imaging benefits from the continued improvements in MR imaging speed. One such technique, vastly undersampled projections in radial direction (VIPR), will increase the speed of CT and MR imaging by a factor of 10 to 50.² This section illustrates the present capabilities for functional imaging of the spine and the possibilities for functional imaging of the spine that have not received sufficient attention from spine researchers. In this short review, dynamic imaging will be emphasized.

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Figure 1. Magnetic resonance images of a dog spine before (left) and 40 minutes after (right) injection of contrast medium intravenously. Contrast enhancement is clearly evident in portions of the intervertebral disc. Enhancement is not detected in the peripheral anulus fibrosus, which consists mostly of collagen, or in the equator of the disc, sometimes referred to as the “intranuclear cleft,” which also has high fiber content. In the images obtained at 5, 10, and 20 minutes after injection of contrast medium (not shown), the enhancement appeared first at the junction of the peripheral and the inner anulus fibrosus and then proceeded toward the central portion of the disc.

■ Contrast Enhancement

The administration of contrast medium intravenously for the purpose of increasing the contrast between tissues in the body (“contrast enhancement”) has been used extensively in CT and MR imaging of the head and body. In the spine, contrast enhancement may be used to study degenerating intervertebral discs and to detect injuries of spinal nerves and roots.

The intervertebral disc normally does not enhance visibly with intravenous contrast medium because the disc lacks vascularity. Normal intervertebral discs increase slowly in signal intensity after the intravenous administration of contrast medium, because contrast medium diffuses slowly into the disc through the endplates (Figure 1). Normal discs in animals increase in signal intensity by as much as 36% after contrast medium administration.⁴ The amount of enhancement is related to the type and amount of contrast medium used and the composition of the intervertebral disc. Intervertebral disc enhancement is diminished when a high molecular weight contrast medium is substituted for the standard medium.⁵ In discs with lower concentrations of glycosaminoglycans, contrast enhancement is more rapid and more intense.⁶ When a radial tear is created experimentally in the disc, contrast enhancement diminishes.⁷ Diffusion into human intervertebral discs can be detected with MR imaging after intravenous administration of nonionic paramagnetic contrast medium.⁸

Contrast enhancement may be detected in some discs immediately after administration of contrast medium. This enhancement is present within a narrow band of

some degenerating intervertebral discs. The enhancement presumably corresponds to a region of disc in which granulation tissue has invaded due to the presence of a radial tear. A radial tear in the anulus fibrosus may be detected as a region of contrast enhancement. It may also be detected in T2-weighted images as a region of high signal intensity (high intensity zone, or HIZ) in a portion of the anulus fibrosus that normally has low signal intensity. Contrast enhancement suggests the presence of granulation tissue within the radial tear, whereas the high signal in T2-weighted images may be due to mucoid material in the radial tear. Neither contrast enhanced images nor T2-weighted images demonstrate radial tears with a high degree of accuracy.

Granulation tissue within a radial tear suggests the presence in the disc of nerve endings, which are normally not present in the intervertebral disc except in the outermost layers. Whether these nerve endings include nociceptors or not has not been determined. Hypothetically, the presence of the granulation tissue indicates the possibility of a pain mechanism within the disc.

Contrast enhancement has also been used to study nerve roots. Normal nerve roots do not enhance normally because of tight junctions in their capillary endothelium that restrict the passage of solutes into the interstitial fluids. The brain and the spinal cord have a similar barrier to diffusion, termed the blood–brain barrier. Injury to the nerve root or cord may result in an opening of the endothelial tight junctions and permeability of the barrier. The disrupted barrier results in contrast enhancement within the nerve root. Contrast enhancement of spinal nerve roots correlates to some degree with the pain pattern in patients with radiculopathy.³ The sensitivity and specificity of nerve root enhancement has not been sufficient to justify the routine use of contrast enhancement in the investigation of radiculopathy.

■ Neurography

The use of high-resolution phased array surface coil T2-weighted imaging to demonstrate signal intensity changes in spinal nerves and spinal nerve roots has been termed “neurography.”⁹ Diminished myelin content or increased water content causes increased signal intensity in a nerve in a neurographic image. Lumbosacral plexus, cervical nerves, and peripheral nerves can be studied with neurography.¹⁰ With neurography, investigators have shown that the signal intensity in peripheral nerves changes with injury and recovery. It has been used to demonstrate abnormal nerve roots in patients with symptoms of radiculopathy (Figure 2).

Application of neurography in patients with chronic pain syndromes is warranted. If demyelination of a spinal nerve is associated with crossed after discharge,¹¹ then neurography should show increased signal intensity in nerves in some patients with radiculopathy secondary to nerve root injury. Neurography may be a useful means to identify demyelinated spinal nerves, and neurographic findings may correlate with pain syndromes. Neurography has the capability *in vivo* to detect nerve injury.^{12,13}

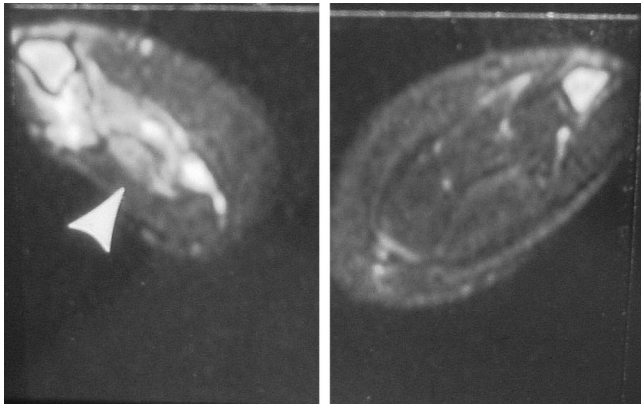


Figure 2. T2-weighted neurography images in a rat, showing the right lower extremity (left) and left lower extremity (right). The images were taken 30 days after the right sciatic nerve was injured proximal to this level by crushing. The image shows high signal intensity in the right sciatic nerve (arrowhead) and in the denervated muscles. No such high signal is identified in the control sciatic nerve on the left.

■ Magnetic Resonance Spectroscopy

Magnetic resonance spectroscopy, which now includes single voxel and multivoxel techniques, has a role in diagnostic imaging. With the single voxel spectroscopy, the concentration of some metabolites can be estimated in a volume of tissue sampled with MRS (Figure 3). In the multivoxel technique, the metabolite concentrations are mapped voxel by voxel within the volume of interest that is sampled. The multivoxel technique allows the metabolite concentration to be displayed as an image (2-dimensional or 3-dimensional chemical shift imaging, or CSI).

Two-dimensional CSI is under investigation for identifying physiologic as well as pathologic changes of the bone marrow¹⁴ and spinal cord. Hypercellularity and myeloid hyperplasia in patients with glycogen storage disease type Ib due to functionally impaired leukocytes results in a strongly increased water proton signal with a very low or absent lipid signal in localized proton MR

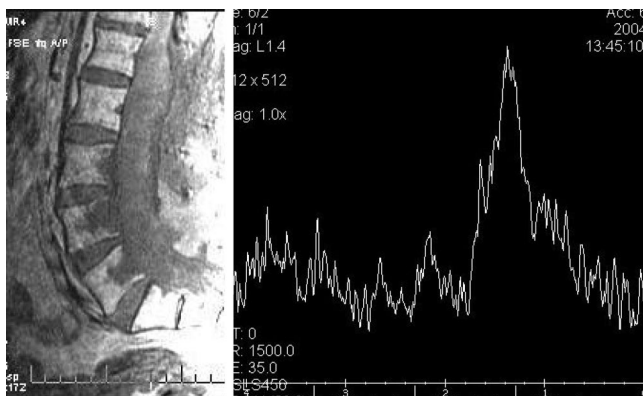


Figure 3. Magnetic resonance spectroscopy or chemical shift imaging illustrating metabolites in a spinal cord tumor. The spectrum reveals a major peak due to the presence of lipids in a necrotic tumor. A creatine peak and an elevated choline peak are also demonstrated. Bone development, intervertebral disc degeneration, and spinal cord disease may be evaluated with MRS.

spectroscopy.¹⁵ Applied to the intervertebral disc, MRS provides the means of detecting noninvasively lactic acid, which increases in degenerating intervertebral discs, especially in those cases with associated dural scarring.¹⁶ Magnetic resonance spectroscopy shows a larger fat fraction in patients with osteopenic bone than in normal bone.¹⁷

Magnetic resonance spectroscopy may also be applied to the study of the spinal cord. In the cord, MRS provides the capability of measuring neuronal integrity as the concentration of N-acetyl aspartate, which is a marker for adult healthy neurons. It also shows the presence of lactic acid, which develops in the spinal cord when anaerobic glycolysis takes place, and the concentration choline, which is a marker for processes characterized by cell proliferation. The continued technological improvement of MRS gradually overcomes the technical obstacles in the spine, which are due to the inhomogeneities of the magnetic field in the spine and the motion of CSF.

■ Imaging Water Content in the Disc

Changes in water content in the disc can be measured as a change in T2 relaxation.^{18,19} In normal discs, the T2 relaxation time is 80 (\pm 19) milliseconds.¹⁸ Diurnal variations in the disc water can be detected by means of the T2 relaxation measurement.²⁰⁻²³ Therefore, T2 measurements likely represent an objective and quantitative means of analyzing disc integrity.

With MR, the direction and amount of water diffusing in each voxel can be measured. The diffusion of water in tissue is anisotropic, that is, diffusion occurs unequally in different directions because of the tissue structure. Diffusion can be measured as a relative amount of water diffusion occurring within a voxel (diffusion-weighted image) or as the direction and magnitude of water diffusion in 3 dimensions in each voxel (diffusion tensor imaging, or DTI). Diffusion imaging provides an important tool for the detection of cerebral infarction, which is associated with cytotoxic edema and reduced diffusion. In the spinal cord, infarction can be detected also by diffusion MR.²⁴ Diffusion imaging of the spine may provide a means for demonstrating early intervertebral disc degeneration (Figure 4).

Diffusion tensor imaging in the brain or spinal cord shows white matter tracts because diffusion along the tracts proceeds more rapidly than diffusion across the tracts. In the intervertebral disc, DTI has been used to study the integrity of the fibers in the annulus fibrosus.²⁵ In the annulus fibrosus, the anisotropic patterns of diffusion correlate with the known collagen fiber architecture. With DTI, defects in the annulus can be demonstrated by DTI (Johan van Goethem, personal communication). Significant differences in magnitude and direction of diffusion are found between compressed and noncompressed intervertebral discs.²⁰ These findings suggest MR diffusion tensor microscopy may be a tool to assess the lamellar structure of the intervertebral disc. Recently developed methods of diffusion imaging promise to improve spine imaging. Line scan diffusion imaging is a

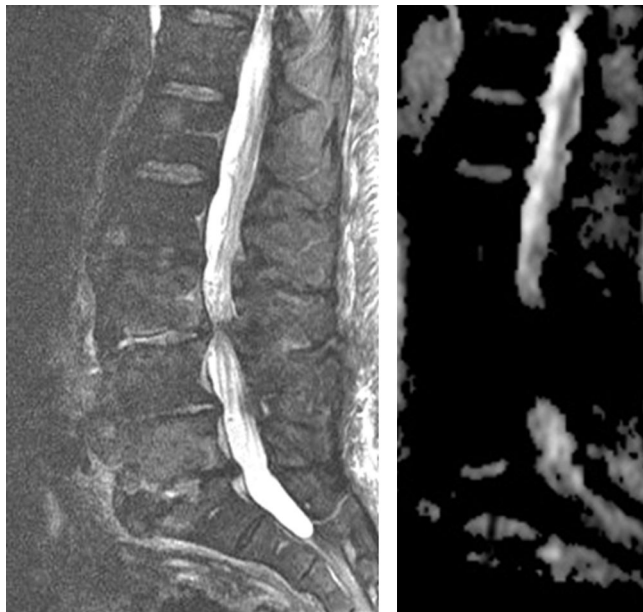


Figure 4. Sagittal diffusion-weighted image of the lumbar spine in a 57-year-old patient with back pain. High signal intensity in intervertebral discs with normal height (L1–L2, L2–L3) indicates restricted diffusion characteristic of healthy cartilage. Lower signal intensity in the other lumbar intervertebral discs indicate a loss of water or less restricted diffusion, consistent with degeneration.

robust and reliable method for imaging the spinal column. It does not suffer as strongly from susceptibility artifacts as does echo-planar imaging or from patient motion as other multishot techniques.²⁶

■ Functional Magnetic Resonance Imaging

With fMRI, the functional organization of the brain is studied noninvasively, and the location of functions is mapped in patients who are selected for some surgical procedures on the brain. This capability can be applied to the spine. Investigators have shown that fMRI can demonstrate neuronal activity in the spinal cord secondary to use of motor or sensory systems. Hypothetically, fMRI may be used in the evaluation of back pain syndromes. With fMRI of the spinal cord, susceptibility artifacts, contrast resolution, and spatial resolution represent technological obstacles.

In one fMRI study, task-dependent signal intensity changes were detected reliably in patients performing an isometric exercise. Although regions of activation were distributed throughout the spinal cord, concentrated activity was found in the anatomic locations of expected motor innervation²⁷ (Figure 5). Functional MRI has also produced reliable maps of neuronal activity that occur secondary to tactile stimulation or median nerve stimulation of the hand and forearm.^{28,29}

Spinal fMRI is also applied to studies of the spinal cord, below the site of an injury. Activation is noted in the spinal cord even when the patient cannot feel the stimulus being applied. Signal intensity changes in paraplegic patients have the same stimulus-response pattern as noninjured patients, but the areas of activity in the spinal gray matter are notably altered. In patients with



Figure 5. Axial image from an fMRI study of the spine illustrating activation from a right L4 dermatome thermal stimulus. Courtesy of Patrick W. Stroman, PhD, University of Manitoba.

complete injuries, activity is absent ipsilateral to the thermal stimulation, but appears to be enhanced on the contralateral side. These findings demonstrate the reliability and clinical potential of spinal fMRI.²⁸

■ Dynamic Imaging

With CT or MR, images of the spine can be acquired in seconds, creating the possibility of monitoring the displacement and rotation in spinal vertebra and changes in disc morphology as a load or torque is applied to the spine or as the patient's position is changed. Rapid imaging to monitor changes in the target tissue is referred to as dynamic imaging. Dynamic imaging of the spine has been used for several purposes: 1) detecting "occult" disc herniation that theoretically disappear when the patient is supine; 2) measuring changes in the dimensions of the neural foramen and spinal canal when the spine is subjected to an axial load or to extension or flexion; and 3) measuring the relative mobility of motion segments.

Various investigators have attempted to demonstrate that with some load or torque applied to the spine in patients with back pain, the nucleus pulposus herniates. Intermittently, reports have appeared on the use of some device to apply a load to the spine to detect such herniation with CT or MR.³⁰ However, such devices have not achieved much popularity. The theory that disc herniations change in size as a load is applied to the spine does not accord with current concepts of intradiscal pressures.

Both *in vivo* and *in vitro*, the application of load to the spine may result in diminished dimensions of the central spinal canal and neural foramen.^{31–33} In theory, some cases of back pain may be explained by "occult" central or lateral stenosis, that is, critical narrowing of the spinal canal or foramen that is not appreciated before the application of the load or position change. Intermittent narrowing of the neural foramen or spinal canal sufficient to compress a spinal nerve may result in an injured nerve and pathologic functioning of the nerve.^{11,34} In a literature review, one group of authors reported that imaging the spine in erect and extended positions or with axial compressions consistently reveals reductions in the

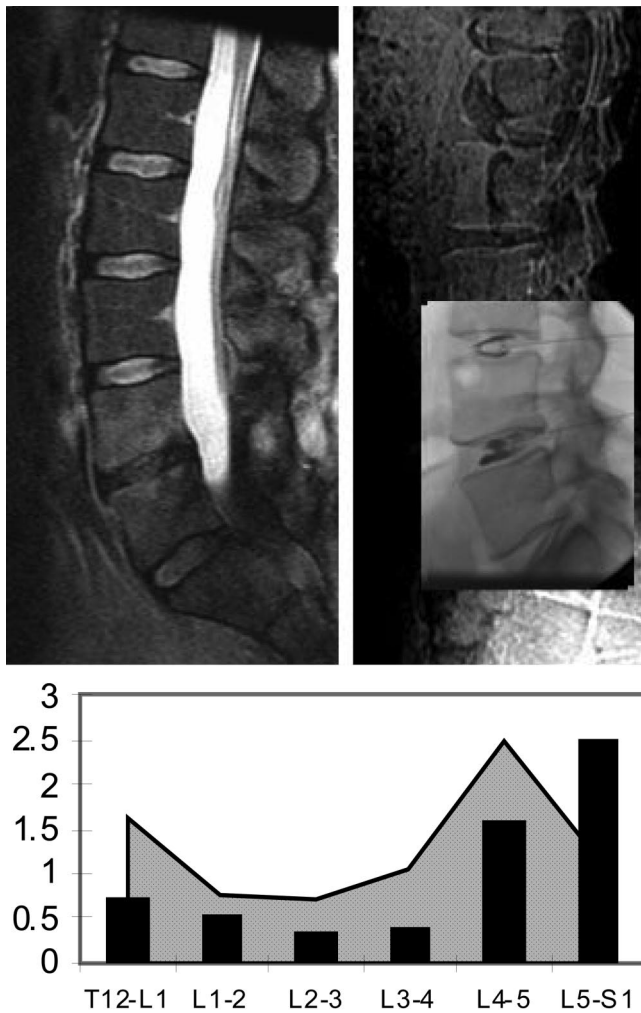


Figure 6. Magnetic resonance image (upper left), radiograph from discogram (upper right) in a patient with back pain. In the graph (bottom), the axial rotations measured at each lumbar vertebra by means of dynamic CT are shown. In this patient, signal intensity was decreased in the L4–L5 and L5–S1 intervertebral discs. At discography, concordant pain was found at L5–S1. Subsequently, a spinal fusion was performed at L5–S1 with a good result. The amount of rotation at each level that occurred with a 16° rotation of the torso is indicated by the height of the bar in the graph. The 95% confidence limit for rotations at each spinal motion segment is shown by the shaded areas in the graph. The normal values are based on a small sample size. Note that the L5–S1 intervertebral disc had excessive motion compared to the motion of normal L5–S1 discs.

dimension of the spinal canal and neural foramen.³⁵ They indicated that these maneuvers may occasionally identify occult nerve root compression, but not commonly. They concluded that effect of such maneuvers on the sensitivity and specificity of MR requires more study.

The possibility of dynamic MRI to measure the relative mobility of motion segments is under evaluation. Roentgen stereophotogrammetry (RSA) has been the standard for measuring the rotations of lumbar vertebrae secondary to changes in body position or loading of the spine.^{36,37} Roentgen stereophotogrammetry has disadvantages that include its expense and invasiveness. Alternatively, changes in axial orientation of vertebrae during loading or changes

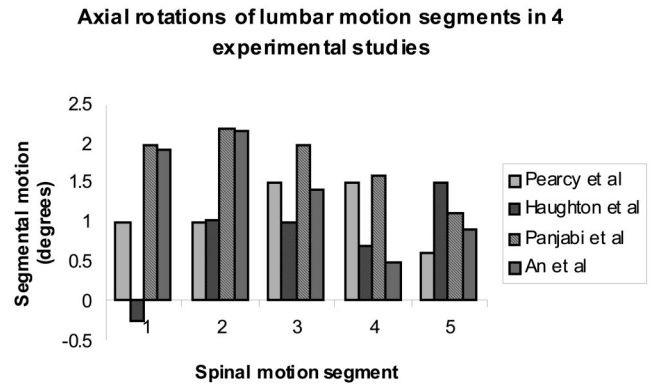


Figure 7. Average motions of the five normal lumbar motion segments that were measured in four studies. Between studies, the relative amount of rotation at each level varies, probably because of the small sample sizes in each study. In all the studies, however, average rotations do generally exceed 2° at any spinal level. Courtesy of Howard An, MD.

in body position may be measured with axial CT or MR images in human patients placed on a specially designed gantry table that applies a torque to the lumbar spine.^{38,39} It can also be performed in scanners that permit the placement of the patient in erect position. However, image quality in such scanners is limited by the need for larger receiver coils and the use of lower field strengths.

Because of their axial image capability, CT or MR accurately demonstrate axial rotations of vertebrae when a load or torque are applied, without the need to place radiographic markers or to employ complicated calculations. An automated program based on a standard image registration algorithm has been developed for the purpose of measuring rotations of the lumbar vertebrae.⁴⁰ The amount of rotation at each level can be calculated accurately to a tenth of a degree⁴¹ from images obtained before and after applying a torque (Figure 6). Axial rotations of lumbar vertebrae have been measured with these techniques in normal patients and in patients with back pain.^{42,43} If patients with “degenerative spinal instability” have greater motion of vertebra than normal or asymptomatic patients after the application of a load to the spine, then dynamic MR and CT studies may have important applications in the evaluation of patients with back pain. Normative data for rotation of discs at each lumbar level are insufficient to determine exactly the threshold between normal and abnormal rotation (Figure 7).

To estimate the potential for dynamic CT or MR to detect clinically significant abnormal motion of the spine, dynamic CT was compared to discography, on the assumption that “concordant pain” has a reasonably good predictive value for instability.⁴³ In this study, the results of dynamic CT had a highly significant correlation with concordant pain (D. Blankenbaker *et al*, unpublished data). Rotation at levels with normal discs averaged 0.5°, whereas rotation at levels with degenerating discs and concordant pain averaged 1.8° under the same conditions. Dynamic CT and MR have the capability of identifying mo-

tion segments with increased rotations. The diagnostic value of dynamic imaging deserves additional study.

■ Conclusions

Spine imaging now includes numerous possibilities for “functional imaging.” These include contrast enhancement, neurography, MRS, DTI, and dynamic imaging. Dynamic imaging in particular appears to offer possibilities for studying the motions of the spine to distinguish abnormal motions that may characterize some chronic pain syndromes. Further investigation of functional spine imaging is warranted.

■ Key Points

- T2 maps, diffusion images and diffusion tensor images, generated from multi-echo MR images, can be used to study water content and structure of the intervertebral disk.
- Dynamic CT or MR imaging shows changes in spine dimensions and magnitude of rotation or translation when a specific load or torque is applied to the spine.
- These new functional imaging techniques promise to improve our ability to diagnose and evaluate intervertebral disk degeneration in patients with back pain.

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