Normal Spinal Anatomy on Magnetic Resonance Imaging

Gaurav Jindal, MD*, Bryan Pukenas, MD

Over the past few decades, spinal magnetic resonance imaging (MR imaging) has largely replaced computed tomography (CT) and CT myelography in the assessment of intraspinal pathology at institutions where MR imaging is available. Given its high contrast resolution, MR imaging allows the differentiation of the several adjacent structures comprising the spine. This article illustrates normal spinal anatomy as defined by MR imaging, describes commonly used spinal MR imaging protocols (Tables 1–3), and discusses associated common artifacts.

SPINAL MR IMAGING TECHNIQUES

Sagittal and axial magnetic resonance images should be acquired through the cervical, thoracic, and lumbar segments of the spine, as they are generally considered complementary, and imaging the spine in only one plane may result in misinterpretation. The addition of coronal images may also be useful, especially in patients with scoliosis. Stacked axial images and/or angled images through the discs can be obtained, often useful when the indication for imaging is pain, degenerative change, and/or radiculopathy. Although imaging in the axial plane is a matter of personal preference, using only angled axial images through the discs may be inadequate, as portions of the spinal canal will not be imaged axially. Slice thickness from 3 to 4 mm is generally optimal for imaging of the spine. Axial gradient-echo images through the cervical spine are typically 2 mm thick.

To depict the fine anatomic detail in the spine, high spatial resolution is a priority because of the small size of the cervical spine relative to the human body and because of the relatively superficial position of the spine within the human body. The use of surface coils, typically phased array receiver coils, helps to maximize signal-to-noise ratio and spatial resolution. Increasing phase-encoding steps results in a larger matrix and higher spatial resolution as a result but also leads to increased imaging acquisition time, which increases the possibility of motion-related image degradation. Among the other factors affecting spinal imaging are matrix size, field of view, gradient moment nulling motion compensation, pulse triggering and gating, band width, and phase-encoding axis.

The pulse sequences used are determined by the clinical indications for the examination based on the following major categories: degenerative disease including radicular symptomatology, trauma, cord compression/bony metastases, and infection. Spin-echo and fast spin-echo sequences are the most common sequences used in spinal MR imaging. Short tau inversion recovery (STIR) imaging is useful to assess the bone marrow and in cases of infectious, inflammatory, and neoplastic lesions. STIR imaging is also useful in the workup of trauma, to assess for ligamentous injury and changes from hemorrhage...
<table>
<thead>
<tr>
<th>Sequence</th>
<th>Localizer</th>
<th>FLAIR</th>
<th>T2</th>
<th>T2</th>
<th>GRE</th>
<th>T1</th>
<th>T1</th>
<th>STIR</th>
<th>Enhanced T1</th>
<th>Enhanced T1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane</td>
<td>3 plane</td>
<td>Sagittal</td>
<td>Sagittal</td>
<td>Axial</td>
<td>Axial</td>
<td>Sagittal</td>
<td>Axial</td>
<td>Sagittal</td>
<td>Sagittal</td>
<td>Axial</td>
</tr>
<tr>
<td>Thickness, mm</td>
<td>10</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>TR, ms</td>
<td>24</td>
<td>1700</td>
<td>3530</td>
<td>4210</td>
<td>32</td>
<td>653</td>
<td>649</td>
<td>4400</td>
<td>653</td>
<td>649</td>
</tr>
<tr>
<td>TE, ms</td>
<td>6</td>
<td>12</td>
<td>106</td>
<td>111</td>
<td>14</td>
<td>10</td>
<td>11</td>
<td>74</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Flip angle</td>
<td>30</td>
<td>150</td>
<td>180</td>
<td>150</td>
<td>5</td>
<td>170</td>
<td>150</td>
<td>150</td>
<td>170</td>
<td>150</td>
</tr>
<tr>
<td>NEX</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Matrix</td>
<td>128 × 256</td>
<td>250 × 384</td>
<td>269 × 384</td>
<td>240 × 320</td>
<td>216 × 320</td>
<td>269 × 384</td>
<td>205 × 256</td>
<td>192 × 256</td>
<td>269 × 384</td>
<td>205 × 256</td>
</tr>
<tr>
<td>FOV read, mm</td>
<td>300</td>
<td>260</td>
<td>240</td>
<td>200</td>
<td>200</td>
<td>240</td>
<td>240</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>FOV phase, mm</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>75</td>
<td>75</td>
<td>200</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Comments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: FLAIR, fluid-attenuated inversion-recovery imaging; FOV, field of view; GRE, gradient-recalled echo; Mets, metastases; NEX, number of excitations; STIR, short tau inversion recovery; TE, echo time; TR, repetition time.
and/or edema. Contrast-enhanced imaging should be used, unless contraindicated, for indications including evaluation of the postoperative spine, suspected infection, or intradural or nontraumatic cord lesions.\textsuperscript{10} Abnormalities within the epidural space identified during unenhanced evaluation for metastases and/or cord compression can be better delineated using contrast-enhanced images.\textsuperscript{10}

Gradient-recalled echo (GRE), or gradient-echo, sequences allow for delineation of bone and disk margins, provide excellent contrast between the spinal cord and surrounding subarachnoid space, and allow clear visualization of the neural foramina and exiting nerve roots. Gradient-echo axial images are used in the cervical and thoracic spine to detect spinal canal and foraminal stenoses\textsuperscript{11} and serve as an important complement to long repetition time spin-echo imaging, given faster acquisition time of GRE. As a result, GRE images are less susceptible to patient motion artifact.

### Table 2

**Thoracic spine MR imaging protocols**

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Localizer</th>
<th>T1</th>
<th>T2</th>
<th>T2</th>
<th>T2</th>
<th>STIR</th>
<th>Enhanced T1</th>
<th>Enhanced T1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane</td>
<td>3 plane</td>
<td>Sagittal</td>
<td>Sagittal</td>
<td>Axial</td>
<td>Sagittal</td>
<td>Sagittal</td>
<td>Axial</td>
<td></td>
</tr>
<tr>
<td>Coil type</td>
<td>Spine</td>
<td>Spine</td>
<td>Spine</td>
<td>Spine</td>
<td>Spine</td>
<td>Spine</td>
<td>Spine</td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>10</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>TR, ms</td>
<td>20</td>
<td>641</td>
<td>3000</td>
<td>7360</td>
<td>3220</td>
<td>670</td>
<td>579</td>
<td></td>
</tr>
<tr>
<td>TE, ms</td>
<td>6</td>
<td>17</td>
<td>100</td>
<td>106</td>
<td>74</td>
<td>14</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Flip angle</td>
<td>30</td>
<td>180</td>
<td>150</td>
<td>150</td>
<td>180</td>
<td>150</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>NEX</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Matrix</td>
<td>128 × 256, 256 × 256</td>
<td>307 × 384</td>
<td>192 × 256</td>
<td>256 × 256</td>
<td>256 × 256</td>
<td>269 × 384</td>
<td>230 × 256</td>
<td></td>
</tr>
<tr>
<td>FOV read, mm</td>
<td>380</td>
<td>300</td>
<td>320</td>
<td>200</td>
<td>320</td>
<td>320</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>FOV phase, mm</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Comments</td>
<td>Trauma, Mets If indicated</td>
<td>If indicated</td>
<td>If indicated</td>
<td>If indicated</td>
<td>If indicated</td>
<td>If indicated</td>
<td>If indicated</td>
<td>If indicated</td>
</tr>
</tbody>
</table>

**Abbreviations:** FOV, field of view; Mets, metastases; STIR, short tau inversion recovery; TE, echo time; TR, repetition time.

### Table 3

**Lumbar spine MR imaging protocols**

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Localizer</th>
<th>T1 FLAIR</th>
<th>T2</th>
<th>T2</th>
<th>T2</th>
<th>T1</th>
<th>STIR</th>
<th>Enhanced T1</th>
<th>Enhanced T1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane</td>
<td>3 plane</td>
<td>Sagittal</td>
<td>Sagittal</td>
<td>Axial</td>
<td>Sagittal</td>
<td>Sagittal</td>
<td>Axial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil type</td>
<td>Spine</td>
<td>Spine</td>
<td>Spine</td>
<td>Spine</td>
<td>Spine</td>
<td>Spine</td>
<td>Spine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>10</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TR, ms</td>
<td>3.27</td>
<td>1600</td>
<td>3150</td>
<td>4250</td>
<td>500</td>
<td>4560</td>
<td>657</td>
<td>539</td>
<td></td>
</tr>
<tr>
<td>TE, ms</td>
<td>1.64</td>
<td>12</td>
<td>95</td>
<td>106</td>
<td>14</td>
<td>79</td>
<td>12</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Flip angle</td>
<td>55</td>
<td>150</td>
<td>180</td>
<td>150</td>
<td>90</td>
<td>180</td>
<td>90</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>NEX</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matrix</td>
<td>115 × 256, 256 × 256</td>
<td>256 × 256</td>
<td>256 × 256</td>
<td>256 × 256</td>
<td>256 × 256</td>
<td>256 × 256</td>
<td>256 × 256</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FOV read, mm</td>
<td>450</td>
<td>280</td>
<td>280</td>
<td>200</td>
<td>200</td>
<td>280</td>
<td>280</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>FOV phase, mm</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>75</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comments</td>
<td>Trauma, Mets If indicated</td>
<td>If indicated</td>
<td>If indicated</td>
<td>If indicated</td>
<td>If indicated</td>
<td>If indicated</td>
<td>If indicated</td>
<td>If indicated</td>
<td></td>
</tr>
</tbody>
</table>

**Abbreviations:** FLAIR, fluid-attenuated inversion-recovery imaging; FOV, field of view; Mets, metastases; STIR, short tau inversion recovery; TE, echo time; TR, repetition time.
GRE, fat is of low signal intensity on GRE sequences compared with T1-weighted spin-echo imaging; as a result, morphologic detail defined by fat is not as well demonstrated on GRE images as on spin-echo images. Proton density images can be obtained simultaneously (TR 2000 to 3000 milliseconds or greater, TE 20 to 90 milliseconds) when obtaining T1-weighted images and can also be derived from an earlier (first) echo while generating T2-weighted images. Proton density images of the spine are not routinely obtained but can provide valuable information concerning normal and pathologic spinal morphology.

NORMAL SPINAL ANATOMY BASICS

The cervical spine comprises the first 7 superior vertebrae of the spinal column. The first and second segments of the cervical spine are unique. The other cervical vertebrae are similar in size and configuration. The first segment, C1, also known as the atlas, is ring shaped and composed of anterior and posterior arches and lateral articular masses. It lacks a central vertebral body. The second segment, C2, also known as the axis, is also ring shaped and has a superiorly oriented odontoid process, also known as the dens, which lies posterior to the anterior arch of C1. The normal distance between the dens and anterior arch of C1 is approximately 3 mm in adults and 4 mm in children. There are prominent tubercles along the medial aspects of the lateral masses of C1 from which extend the transverse portion of the cruciate/cruciform ligament, ie, the transverse ligament, which confines the odontoid process of C2 posteriorly and delineates the anterior and posterior compartments. This relationship allows free rotation of C1 on C2 and provides for stability during upper cervical spinal flexion, extension, and lateral bending. The transverse ligament is covered posteriorly by the tectorial membrane. The alar ligaments are paired winglike structures connecting the lateral aspects of the odontoid process with the occipital condyles. The thin apical ligament of the odontoid process directly anchors the tip of the odontoid process to the clivus in the anterior aspect of the foramen magnum. The tip of the odontoid process is anterior to the lower medulla. A line of low T1-weighted signal intensity seen through the base of the dens represents the subdental synchondrosis, present in many healthy individuals; it may be distinguished from a fracture because the synchondrosis does not extend to the adjacent cortical bone (Figs. 1 and 2).

Unique to the cervical spine, the bilateral uncovertebral joints, also referred to as Luschka joints, are formed by articulation of the uncinate process of the inferior vertebral body with the uncus of the superior vertebral body (see Fig. 2; Figs. 3 and 4). The uncus is a cup-shaped groove on the posterior/inferior aspect of each cervical vertebral body (except C1), whereas the uncinate processes are located bilaterally on the posterosuperior aspects of the cervical vertebral bodies (except for C1 and C2). The cervical vertebrae also form transverse foramina bilaterally through which the vertebral arteries pass. Although the C7 vertebral body forms transverse foramina, the vertebral arteries usually enter the foramina at C6. The vertebral arteries are seen as circular low-signal structures owing to the flow-void phenomenon (see Fig. 3B). The spinous processes of the cervical spine are short and have bifid tips. Compared with the lumbar disks, the disks of the cervical and thoracic spine are much thinner and the outermost portion of the anulus is not as thick.
The cervical spine is depicted in images in Figs. 1–5 and Fig. 6.

Given the anterolateral-directed obliquity of the cervical neural foramina, oblique sagittal views are required to view cross-sectional sagittal anatomy of the neural foramina of the cervical spine.\(^\text{14,15}\) These images are obtained by using an axial image to first assess optimal angulation of the oblique sagittal plane through the foramina.

Throughout the spine, the intervertebral canals, or neural foramina, contain the nerve root and its sleeve, the dorsal root ganglion, fat, and blood vessels. The neural foramina are bounded anteriorly by the vertebral bodies and disc, superiorly and inferiorly by the pedicles, and posteriorly by the facet joints which are covered by the ligamentum flavum (see Fig. 3).\(^\text{16}\) The segmental osseous structures of the spine include the vertebral bodies and their appendages, including the pedicles, the articular pillars, laminae, and transverse and spinous processes. The major ligaments of the spine are the anterior longitudinal ligament, posterior longitudinal ligament, and ligamentum flavum (Fig. 7).\(^\text{16}\) The spinal canal contains the thecal sac enclosed by the dura mater and surrounded by the epidural space, which contains epidural fat and a large venous plexus. Within the thecal sac are the spinal cord, conus medullaris, and cauda equina, surrounding by freely flowing cerebrospinal fluid (CSF) within the subarachnoid space. The conus medullaris normally terminates near the L1 vertebral level.\(^\text{16}\) In the supine position,
the nerve roots of the cauda equina in the lumbar spine are clustered in the dependant/posterior aspect of the spinal canal (Figs. 8 and 9).

The posterior border of nearly all of the vertebral bodies is flat or slightly concave when viewed in axial section and the discs do not normally extend beyond the margins of the adjacent vertebral bodies. However, with exaggerated extension, 1-mm to 2-mm budging may occur in some histologically normal disks. The posterior margins of the discs tend to be slightly concave in the upper lumbar spine, straight at the L4/5 level, and slightly convex at the lumbosacral spinal junction. This appearance should not be confused with pathologic bulging. The axial appearance of the L5 vertebral body is biconcave shaped, and iliolumbar ligaments emanate laterally from L5, characteristics that allow distinction of this vertebral segment from others when viewed in the axial plane (see Fig. 9). The spinal canal is round in the upper lumbar region and transitions to a triangular configuration in the lower lumbar region. Posterior epidural fat is consistently present in the posterior part of the spinal canal, whereas the anterior epidural fat is most prominent in the L5-S1 region (see Fig. 8).

The bony canals of the neural foramina are normally well seen en face in the lumbar region using standard sagittal images (Fig. 10) because the orientation of the neural foramina in the lumbar spine is nearly directly lateral as opposed to the anterolateral angle of the neural foramina of the cervical spine. This is in distinction to the anterior obliquity required to optimally visualize the neural foramina of the cervical spine in the sagittal plane.

NORMAL SPINAL ANATOMY, T1-WEIGHTED MR IMAGING

T1-weighted images (TR 300 to 500 milliseconds, TE 20 to 30 milliseconds) in the sagittal plane are obtained as the preliminary survey pulse sequence for analyzing the cervical, thoracic, and lumbar spine. Sagittal and axial T1-weighed sequences provide the anatomic detail with which to begin a survey of the spine.

On T1-weighted images, high signal intensity is demonstrated in mature bone marrow and the epidural fat. Normal bone marrow signal is usually homogeneous but may be heterogeneous and
normally changes with aging. The basivertebral venous channel is seen on the midline sagittal images as high signal within the posterior aspect of the vertebral body owing to fat surrounding the vein (see Fig. 8). Peripherally, bone marrow is surrounded by low signal, proton-poor cortical bone, making it indistinguishable from the adjacent low T1-weighted signal intensity of the annulus fibrosus, spinal ligaments, and dura (Fig. 6). The relatively poor distinction between...
these structures on spin-echo imaging of the cervical and thoracic spine is attributable to little anterior epidural fat compared with that in the lumbar spine (see Figs. 6 and 8). Spin-echo imaging often also poorly differentiates cortical osteophytes from disc material. The anterior and posterior longitudinal ligaments adhere to the fibers of the annulus and will appear on mid-sagittal images as an uninterrupted band of very low signal intensity on all pulse sequences (see Figs. 8 and 10).\textsuperscript{21}

The intervertebral discs demonstrate slightly less signal than the adjacent vertebral bodies and differentiation of the centrally located nucleus pulposis and peripheral annulus fibrosis of the discs cannot be made precisely on T1-weighted images (see Figs. 8 and 10).\textsuperscript{21}

The facet joints appear as linear structures with intermediate signal owing to the presence intra-articular hyaline cartilage and synovial fluid (see Fig. 9).\textsuperscript{22} The facet joint is formed by the concave surface of the superior articular process and the convex surface of the inferior articular process (see Fig. 10). The superior facet is located anterolaterally and faces posteromedially. The inferior facet is located posteromedially and faces anterolaterally. This differs in the cervical spine where the superior and inferior articular processes are fused on either or both sides to form articular pillars, columns of bone that project laterally from the junction of the pedicle and lamina. The bony processes of the spine are better delineated on CT as compared with MR imaging. The ligamentum flava, which bilaterally cover the inner surface of the lamina and the anterior aspects of the facet, joints, are intermediate in signal intensity and are distinguishable from the adjacent high-signal central epidural fat and adjacent peripheral low-signal lamina (see Fig. 9; Fig. 11).

NORMAL SPINAL ANATOMY, T2-WEIGHTED MR IMAGING

The parameters of T2-weighted imaging include a TR of 2000 to 3000 milliseconds and a TE of 60 to 120 milliseconds; the acquisition time is 2 to 3 times longer than that of T1-weighted imaging, rendering T2-weighted imaging more susceptible to motion artifact and greater noise.

In general, T2-weighted images reveal greater contrast differentiation among structures in comparison with T1-weighted images. With T2 weighting, the proton-poor cortical bone demonstrates low signal intensity and the bone marrow remains fairly high in signal intensity because of its fat content. The basivertebral veins may be of even higher signal intensity because of flow phenomena and should not be mistaken for a fracture (Fig. 12). The channel of the basivertebral vein is usually of intermediate signal on the T2-weighted image. The normally hydrated nucleus pulposus composed of water and proteoglycans shows high T2-weighted signal centrally with lower signal from the less-hydrated annulus fibrosis (see
The annulus fibrosis is composed of fibrocartilage centrally, whereas the outer fibers are made of concentrically oriented collagen fibers. The annulus is anchored to the adjacent vertebral bodies by Sharpey fibers, which are normally not visible by MR imaging.

CSF demonstrates high signal intensity because of its long T2-weighted relaxation time, which allows sensitive identification of surrounding intraspinal structures such as the spinal cord and nerve roots that are intermediate in signal intensity (see Fig. 12; Figs. 13–15). When the patient is supine, as in most cases of spinal imaging, the midthoracic spinal cord is positioned within the central/anterior aspect of the spinal canal owing to the normally mild thoracic kyphosis (see Fig. 12). CSF often has patchy areas of low signal because of turbulence of flow and/or other flow artifacts related to pulsation effects; these can be particularly troublesome in images with longer echo delays and in those acquired using high magnetic field strength systems (see Fig. 14).
T2* images intensify structures with long T2 relaxation times such as CSF, the nucleus pulposis, and facet joint cartilage. On T2* images, the high signal intensity of the venous plexus posterior to the vertebral body separates the posterior longitudinal ligament and cortical bone of the vertebral body. T2* imaging also allows differentiation of the gray and white matter of the spinal cord. Gray matter appears as a butterfly-shaped region of high signal intensity centrally within the spinal cord when using this technique.\(^2\)

NORMAL SPINAL BONE MARROW MR IMAGING

The axial skeleton contains red marrow, a major site of hematopoiesis throughout life. There is normally a gradual conversion of red marrow to fatty marrow in the appendicular skeleton, which is completed by approximately 25 years of life. The red marrow in the vertebrae also normally undergoes conversion of fatty marrow, although more subtly than in the appendicular skeleton. The fat content of the vertebral body varies with age, degeneration of adjacent discs, therapy, such as radiation, and increased hematopoiesis in processes such as sickle cell disease or other diseases affecting the bone marrow.\(^2\)

Younger patients, high-signal fatty marrow can be seen as linear areas adjacent to the basivertebral vein. With advancing age, fatty marrow may appear bandlike, triangular, or multifocal and may take up relatively large areas of the vertebral body in patients older than 40.\(^2\) There is significant variability in the marrow pattern among adults and even within an individual.\(^2\)

Ricci and colleagues\(^2\) identified several patterns of marrow distribution in the spine. In pattern 1, the vertebral body demonstrates uniformly low signal on T1-weighted images except for linear areas of high, fatty signal surrounding the basivertebral vein. In pattern 2, bandlike and triangular areas of high signal are found near the end plates and corners of the vertebral body, possibly related to mechanical stress near the end plates. In pattern 3, there are diffusely distributed areas of high signal from fat measuring a few millimeters (pattern 3a) or relatively well-marginated areas on the range of 1 cm (pattern 3b).

In the cervical spine, pattern 1 is found predominantly in patients younger than 40 with patterns 2 and 3 in those who are older than 40. Patterns 2 and 3 generally develop earliest in the lumbar spine, followed by the thoracic spine, and lastly in the cervical spine.\(^2\) Overall, there is continued gradual replacement of hematopoietic marrow with fatty marrow that continues until death. Healthy elderly patients have marked high signal throughout the vertebral body, reflecting the predominance of fatty marrow. Large variations...
exist, however, secondary to differences among individuals and responses to mechanical stress. Chemical shift artifact, used extensively in imaging of the adrenal glands and the liver, can be used to assess the bone marrow of the spine in certain instances. In-phase/opposed-phase imaging assesses for the presence of fat and water in a voxel of tissue. The technique takes advantage of the fact that water and fat protons precess at different frequencies and without a refocusing pulse, when there are both fat and water protons in a given voxel, there will be some signal intensity loss on images that are obtained when the protons are in their opposed phase. The utility of chemical shift imaging lies in the fact that in cases of spinal neoplastic disease, normal fat-containing marrow is replaced with tumor, which can result in lack of signal suppression on the opposed phase images. There have been a few reports that have described in-phase/opposed-phase imaging of the spinal bone marrow.

MR IMAGING FINDINGS OF VERTEBRAL HEMANGIOMAS

Hemangiomas, composed of angiomatoid fibro adipose tissue interspersed among tortuous thin-walled sinuses, are the most common benign tumors of the spine, seen in 10% or more of healthy adults. They are most common in the thoracic spine followed by the lumbar spine and are relatively rare in the cervical spine. They tend to be well-circumscribed tumors within the vertebral bodies demonstrating high signal intensity on both T1-weighted and T2-weighted images. The T1 shortening is produced by the fatty component, whereas the T2 prolongation is produced by the angiomatous component. The very low signal of the bony trabeculae, which can classically be seen on CT, is overshadowed on MR imaging by the signals from the internal elements described previously. Focal fatty infiltration, a common marrow variant, may be confused with hemangiomas on T1-weighted images; however, the expected corresponding decrease in signal intensity on T2-weighted images serves to distinguish focal fat from the normally high T2-weighted signal of hemangiomas. Hemangiomas may sometimes have a paucity of fatty elements, which may render these lesions isointense or hypointense on T1-weighted images.

NORMAL MR IMAGING OF INTERVERTEBRAL DISCS

In the neonate, the nucleus pulposis is a highly gelatinous, translucent, relatively large, ovoid structure. The anulus fibrosus consists of dense fibers organized as concentric lamellae similar to tree rings. In the second decade of life, the outer portion of the disc is replaced by solid tissue and the anulus becomes more dense. In adults, the nucleus pulposis consists of amorphous fibrocartilage and the anulus becomes even more dense. The demarcation between the nucleus and anulus becomes less distinct with age. In adults, a transversely oriented band of low signal intensity in the midportion of the disc represents a fibrous plate visible on MR imaging. Concentric tears of the anulus are seen in normal discs, and transverse tears, although a manifestation of degenerative disease, are not infrequently seen in asymptomatic adults.

Intervertebral herniation of disc material may remodel the vertebral end plate or may extend into the vertebral body. Such herniations are typically referred to as Schmorl nodes. This type of herniation is presumed to have little clinical significance, and it has been observed as early as the second decade of life.

There are abnormalities and normal variants that may mimic the appearance of an extruded or sequestered disk on MR imaging. These include synovial cysts, dilated nerve root sleeves (arachnoid diverticulae), perineural cysts, conjoined nerve roots, nerve sheath tumors, and foreign material such as bullet fragments, metallic hardware, and cement from vertebroplasties. Dilated nerve root sleeves demonstrate signal characteristics identical to CSF, which should allow for differentiation of these from disk material.

COMMON NORMAL SPINAL MR IMAGING ARTIFACTS

The most common source of artifact in MR imaging occurs secondary to patient motion. Whereas random movement leads to blurring, periodic motion, such as with CSF pulsation, cardiac motion, and respiratory motion, leads to ghosting artifacts in the form of image harmonics along the phase-encoding direction because phase information is acquired over an entire scan (minutes), whereas frequency information is acquired over a single frequency readout (milliseconds).

CSF flow-related phenomena can be divided into time-of-flight (TOF) effects and turbulent flow, which produces dark signal. TOF effects are divided into TOF signal loss resulting in dark CSF signal and flow-related enhancement producing bright CSF signal. TOF loss typically occurs in spin-echo or fast spin-echo imaging when protons do not experience both the initial radiofrequency pulse and the subsequent radiofrequency
TOF loss effects are more pronounced (darker signal) with faster proton velocity, thinner slices, longer TE, and an imaging plane perpendicular to flow. Gradient-recalled echo techniques are less susceptible to TOF loss because of the short TE.

Typical locations for TOF losses include the lateral ventricles just superior to the foramen of Monro, the third ventricle, the fourth ventricle, and within the cervical and thoracic spinal canal. Given the positive relationship between CSF velocity and TOF losses, this effect is magnified in individuals with an underlying abnormally hyperdynamic state, such as hydrocephalus. In addition, laminar flow results in peripherally located protons moving at a slower velocity and leads to a reduction in TOF losses. Turbulent flow results in a broader spectrum of proton velocities and a wide range of flow directions that are not seen in typical laminar flow. This results in more rapid dephasing and signal loss termed “intravoxel dephasing.” A commonly encountered CSF flow artifact is the signal void in the dorsal subarachnoid space on sagittal T2-weighted images of the thoracic spine owing to a combination of the respiratory-related and cardiac-related pulsatile CSF flow superimposed on cranially directed bulk CSF flow and turbulent flow from CSF moving from the ventral subarachnoid space to the dorsal subarachnoid space (see Fig. 14; Fig. 16).

Another common artifact that occurs normally on MR imaging relates to chemical shift and occurs because water and fat protons resonate at slightly different frequencies because of the effects of their local magnetic environment. The most common type of chemical shift artifact occurs along the frequency-encoding axis and results in a spatial misregistration. In the spine, this artifact is manifested as artifactual black lines along the frequency-encoding axis and is most evident in the sagittal T1-weighted images where they produce asymmetric thicknesses of the vertebral end plates. The hyaline cartilage end plate is usually difficult to visualize on MR imaging owing to overlap from chemical shift artifact. Phase-encoding and frequency-encoding gradients may be reversed for imaging the spine in the sagittal plane to avoid chemical shift artifacts in the end plates and disks from the discovertebral interfaces. Chemical shift is proportional to the magnetic field strength.

Truncation artifact, known as Gibb phenomenon, is seen as bands parallel to the spinal cord. This occurs at the interface of CSF and spinal cord because of high-contrast boundaries and is related to acquisition parameters, such as FOV and voxel size (Fig. 17).
SUMMARY

Spinal MR imaging is an excellent tool for identifying details of spinal anatomy, including the intraspinal contents, neural foramina, joints, ligaments, intervertebral discs, and bone marrow. The cortical bony structures of the spine, as elsewhere in the body, are generally better imaged using CT. Motion-related and flow-related artifacts may occur during spinal MR imaging and should not be mistaken for pathology. As advancements continue to be made in both MR imaging hardware and software, spinal MR imaging can continue to expand its role in the delineation of both normal and abnormal spinal anatomy.

REFERENCES