Imaging of Stress Fractures of the Spine

Naveen S. Murthy, MD

KEYWORDS
- Stress fracture  •  Insufficiency fracture  •  Vertebral body  •  Pars interarticularis  •  Pedicle  •  Sacrum

KEY POINTS
- The fluid sign on magnetic resonance (MR) imaging corresponds to the intravertebral vacuum cleft sign on computed tomography (CT) and can be seen in 40% of osteoporotic vertebral compression fractures.
- Secondary radiographic signs of spondylolysis include lateral deviation of the spinous process, unilateral pedicle sclerosis in cases of unilateral pars interarticularis defects, and spinal dysraphism.
- Combined single-photon emission CT (SPECT)/CT has been shown to be useful in the diagnosis of spondylolysis by assessing both metabolic activity and structural components.
- MR imaging with appropriate imaging sequences can be used as an effective and reliable first-line imaging modality for the diagnosis of juvenile spondylolysis with the advantage of not imparting ionizing radiation.
- MR imaging has a reported 100% sensitivity in detecting sacral stress fractures.

INTRODUCTION

Back or limb pain may result from a wide variety of etiology, which are described elsewhere in this issue on spine imaging. Etiology that should not be ignored are stress fractures, fatigue or insufficiency, which may present with minimal, unrecognized or repetitive trauma. The patient population usually determines the type of stress fracture and its location. On a basic level, younger patients typically suffer fatigue fractures as a result of repetitive trauma to bone with normal bone mineral density, whereas older patients typically suffer insufficiency fractures as a result of normal stresses applied to bone with reduced bone mineral density.

Stress fractures intrinsic to the spine that can manifest as back pain may involve the vertebral bodies, pars interarticularis, or the pedicles. Sometimes, stress fractures from the sacrum or bony pelvis may mimic low back pain and may be overlooked. The imaging workup of patients with suspected back pain from stress fractures can be challenging regarding selecting the most appropriate study that best depicts the area of interest and minimizes ionizing radiation and economic costs. This article reviews the relevant imaging literature and provides guidance in this evaluation.

SPINE: VERTEBRAL BODY

It was estimated in 2005 that more than 2 million osteoporotic (insufficiency) fractures occurred annually in the United States in patients older than 50 years; this results in a cost of least $17 billion dollars. Of these fractures, 27% constitute vertebral fractures. By 2025, these costs are expected to increase by 50%, with a rapid growth of fracture rates in individuals between 65 and 74 years of age and in non-White populations. These figures are certainly underestimations, because there are many osteoporotic vertebral compression fractures...
that remain asymptomatic. Cooper and colleagues\(^2\) in a population-based study from Rochester, MN, found that 59% of vertebral fractures occurred without a single traumatic episode. Although non-painful fractures may not pose an immediate problem, the real potential of sustaining additional fractures or progression to painful fractures is of larger concern. Each compression fracture of a wedged configuration adds to kyphotic deformity and places additional stress on the anterior aspect of adjacent or regional vertebrae. One study found that women who had one or more age-indeterminate vertebral body compression deformity at baseline had a 5-fold increased risk of sustaining another vertebral fracture within 1 year.\(^3\) The clinical consequences of osteoporotic vertebral fractures include, but are not limited to, a decrease in mobility, inability to perform activities of daily living, reduced pulmonary function, and chronic back pain.\(^4\)–\(^6\) For these reasons, it is imperative that an accurate and timely diagnosis be made to prevent further injury, morbidity, and socioeconomic costs.

**Radiographs**

Initial evaluation of suspected vertebral body compression fractures should include weight-bearing anterior-posterior (AP) and lateral radiographs. The radiographs allow for assessment of the spinal alignment and relative vertebral body height. They can also be used to follow a fracture with nominal radiation and monetary cost. Care must be taken to obtain a true lateral radiograph, especially in patients without a spine curvature or scoliosis, to avoid potential parallax error, which can falsely produce or falsely estimate a compression deformity. Another potential pitfall is recognizing normal developmental variants such a slight wedge morphology at the thoracolumbar junction and a Cupid’s bow (Fig. 1), which is a biconcave deformity involving the posterior aspect of the inferior endplates of the lumbar spine best seen on the AP radiographs.

One classification that allows for semiquantitative differentiation of vertebral fractures is a method initially described by Genant and colleagues (Fig. 2).\(^7\) This method has been shown to have excellent reliability between radiologists and is known to many clinicians dealing with metabolic bone disease.\(^8\) In this method, a vertebral body between T4 and L4 with more than 20% loss of height and a reduction of area of more than 10% to 20% compared with a normal adjacent segment was considered fractured. Four fracture grades were established: grade 0 (no loss of vertebral body height); grade 1 (vertebral body loss of height 20%–25%); grade 2 (vertebral body loss of height 25%–40%); and grade 3 (vertebral body loss of height >40%). The anterior wedge deformity and the central, biconcave deformity can be seen with osteoporotic fractures. However, a posterior wedge deformity or crush fracture raises concern for a neoplastic etiology.\(^9\) In one cadaveric study, 2 adjacent vertebral bodies from T9 to L4 were loaded to failure at 2\(^\circ\) to 6\(^\circ\) of flexion.\(^10\) Approximately 89% of the resultant fractures involved the superior endplate in all specimen ages. Furthermore, the investigators found that the superior endplates were thinner than the inferior endplates, with the central most regions being the thinnest and supported by less dense trabecular bone.\(^10\) These findings support the observation that an anterior or central vertebral compression deformity is the result of a more physiologic process, whereas a posterior vertebral deformity may be the result of a neoplastic process. Intervertebral disc age-related degeneration also plays a role in the location of a vertebral fracture. Another cadaveric study

![Fig. 1](image-url). Normal variant biconcave deformity involving the posterior aspect of the inferior endplates of the lumbar spine (A, dashed white line). This variant has the appearance of Cupid’s bow on the AP radiograph and should not be confused with a vertebral fracture (B, dashed white line, bow pointing upward).
showed that anterior vertebral bodies of thoraco-lumbar segments involved with intervertebral disc degeneration were associated with relatively less loading in an upright position.\textsuperscript{11} The reduced load bearing of the anterior vertebral bodies resulted in locally reduced bone mineral density, which produced compression failure in flexion at reduced load levels.\textsuperscript{11} It has been proposed that a concave posterior border of the vertebral body suggests a benign etiology, whereas a convex posterior border suggests a malignant etiology.\textsuperscript{9,12} However, 20% of osteoporotic fractures have a posterior convex border.\textsuperscript{12}

The acuity of the compression deformity may be challenging or impossible to ascertain without comparison radiographs taken in close temporal relationship. Acute fractures may show increased density along the compressed endplate, whereas subacute fractures may show callus formation in addition to increased endplate density (Fig. 3).

**Fig. 2.** Vertebral fracture grading by Genant and colleagues\textsuperscript{7}: grade 0 (no loss of vertebral body height); grade 1 (vertebral body loss of height 20\%–25\%); grade 2 (vertebral body loss of height 25\%–40\%); and grade 3 (vertebral body loss of height more than 40\%). (Courtesy of Mayo Clinic, Rochester, Minnesota; with permission.)

**Fig. 3.** Subacute L4 osteoporotic compression fracture. (A) Increased density along the compressed superior endplate of L4 in an 85-year-old woman who experienced the onset of low back pain 2 months earlier. (B) Corresponding sagittal STIR MR imaging taken at the time of the radiographs showing mild bone marrow edema and tiny fluid along the fracture also compatible with a subacute timeframe.
Chronic fracture deformities either from remote trauma or osteoporotic fracture may show remodeling of marginal osteophytes, if present. Although these findings are helpful, they are not pathognomonic. The degree of demineralization can make evaluation of subtle compression deformities, density changes, and callus formation difficult. As one retrospective study showed using nuclear medicine bone scans as the gold standard, osteoporotic vertebral fractures from T4 to L5 could be confidently diagnosed on radiographs only if the compression deformities were more than 3 standard deviations less than the normal mean vertebral height ratios, which were obtained from healthy women between 40 and 65 years of age without osteoporosis. The sensitivity shortcomings of radiographs in diagnosing occult symptomatic osteoporotic vertebral fractures was further shown by Pham and colleagues. These investigators presented a retrospective review of 21 vertebral fractures in 16 patients with no noteworthy vertebral compression deformities on radiographs but who all had positive magnetic resonance (MR) imaging examinations compatible with vertebral insufficiency fractures.

For those symptomatic individuals who have a visible deformity on radiographs, and no recent comparison examination to assess acuity, dynamic sitting and bolstered supine lateral radiographs may be helpful in identifying mobile osteoporotic vertebral fractures that may benefit from treatment (vertebroplasty or surgery). Chen and colleagues studied 105 patients (62–90 years of age) with 144 MR imaging-proven edematous osteoporotic vertebral compression fractures. These investigators found 126 (88%) of the fractures to be mobile on dynamic radiographs, with an average increase in anterior vertebral height from the sitting to bolstered supine position to be 8.5 mm. The overall sensitivity of this radiographic assessment for identifying painful, mobile osteoporotic vertebral compression fractures was 88%. Although this finding is helpful in identifying patients who would benefit from treatment, the investigators caution that this is not a substitute for MR imaging. Preprocedure MR imaging before vertebral augmentation has also been shown to be beneficial by changing the therapeutic plan in 57% of patients as a result of identifying malignancy, accurately localizing or excluding levels of treatment based on bone marrow edema, and finding alternate spatially related diagnoses. The dynamic radiographs may be useful for screening and in the immediate preprocedure time period (if an MR imaging examination was not recently performed) to assist in detecting new fractures, estimating postprocedure height change, and to help determine the feasibility of vertebroplasty in vertebra plana.

**MR Imaging**

As alluded to in the preceding paragraphs, MR imaging can be useful in evaluating age-determinate, occult, and pathologic vertebral fractures. Standard MR imaging sequences should include sagittal T1-weighted and T2-weighted fat-suppressed or short tau inversion recovery (STIR) and axial T2-weighted images. The latter sequence is helpful to assess for paravertebral soft tissue edema or mass. The presence and degree of bone marrow edema suggest the acuity and severity of the fracture. The bone marrow edema pattern is typically bandlike, paralleling the fractured endplate, with some preservation of marrow fat. The presence of a linear low-signal-intensity line within a zone of bone marrow edema can add confidence in the assessment of a fracture (Fig. 4).

MR imaging can also be helpful in aiding in the detection of other potential causes of back pain, such as the predictors of discogenic pain described elsewhere in this issue by Aprill and Maus, intervertebral disc herniation, and the less frequent, but most important, diagnosis of a neoplastic process. A malignant etiology should be considered when there is complete bone marrow replacement manifested as T1 hypointensity, involvement of the posterior elements, osseous destruction, surrounding soft tissue component, presence of additional lesions, and involvement of the upper cervical spine. A single finding in isolation may not be specific for malignancy, but when multiple of these imaging signs are present, the findings can be diagnostic.

One finding that seldom occurs with metastatic vertebral compression fractures, and strongly suggests a benign compression, is the fluid sign. The fluid sign can be seen in 40% of osteoporotic vertebral compression fractures with bone marrow edema; it describes a typically linear zone of fluid signal intensity similar to that of cerebrospinal fluid adjacent to the fractured endplate (see Fig. 4B; Fig. 5). It has been shown that this fluid sign on MR imaging corresponds to the intravertebral vacuum cleft sign seen occasionally with osteoporotic vertebral fractures on radiographs and CT (Fig. 6). Lin and colleagues’ explanation for the basis of this relationship is that in an upright position, the fracture cleft collapses and is mainly filled with fluid. As the spine is extended in the supine position, the distractive force produces negative pressure, pulling nitrogen gas into the cleft.
Depending on the length of time this position is maintained, the cleft is slowly replaced with transudative fluid from the surrounding bone marrow edema.\(^\text{18}\)

If standard techniques cannot exclude a malignant etiology, advanced MR imaging sequences can be performed. These techniques include diffusion-weighted and chemical shift imaging. Diffusion-weighted imaging is based on the Brownian movement of water molecules. Extracellular water, which is mainly seen with osteoporotic fractures, has a higher diffusion capability than the intracellular water.

**Fig. 4.** L2 and L3 osteoporotic compression fractures. (A) T1-weighted MR imaging shows bands of decreased T1 signal within the fractured endplates of the vertebral bodies paralleling the L2 to 3 intervertebral disk (white arrows). There are small scattered areas of preserved marrow fat within these bands consistent with a benign etiology. (B) T2-weighted fat-saturated MR imaging reveals a horizontally oriented linear low signal abnormality within the anterior aspect of the L3 vertebral body paralleling the L2 to 3 intervertebral disk, representing the fracture line of the endplate (dashed white oval). Fluid signal cleft adjacent to the fractured endplate of L2, representing the fluid sign, which can be seen with osteoporotic compression fractures (white arrow).

**Fig. 5.** T2-weighted MR imaging with a fluid signal cleft adjacent to the fractured inferior endplate of L5, representing the fluid sign, which can be seen with osteoporotic compression fractures.

**Fig. 6.** Intravertebral vacuum cleft sign. Nitrogen gas within a benign, osteoporotic vertebral fracture of T9. (Courtesy of Louis Shulman, MD.)
increased intracellular water that occurs with neoplastic processes. Because of the ease of dispersion of extracellular water in osteoporotic vertebral fractures, there is relatively greater loss of signal of the extracellular water when compared with the intracellular water content of neoplastic processes. Tissues with prolonged T2 relaxation can manifest as increased signal on the diffusion-weighted images, simulating a neoplastic process. This phenomenon is known as T2 shine-through. To avoid this pitfall, the apparent diffusion coefficient maps must be assessed along with the diffusion-weighted images and conventional fast spin echo sequences to accurately assess for a neoplastic process. Chemical shift imaging can detect the presence of microscopic fat, which should be preserved in osteoporotic fractures and replaced in pathologic fractures. Preserved microscopic fat shows a loss of signal on the out-of-phase images when compared with the in-phase images. A signal drop-out threshold of 35% has been shown to have a sensitivity of 95% and a specificity of 100% for the presence of microscopic fat in a benign fracture.

**Computed Tomography**

For individuals unable to undergo an MR imaging examination, computed tomography (CT) may be a useful alternative. Although CT is less sensitive for assessing marrow disease, preservation of the trabeculae in nonfractured regions can be helpful in excluding an infiltrating neoplastic process (Fig. 7). The cortical margins are better depicted with CT than MR imaging, and therefore destructive processes and posterior convexity of the vertebral body suggestive of a neoplastic process can be assessed as on MR imaging. The intravertebral vacuum cleft discussed earlier, a sign of a benign process, is better depicted with CT (see Fig. 6).

**Nuclear Medicine Imaging**

Although the bone scan is sensitive for bone turnover, it is not specific for etiology. In regards to the acuity of an osteoporotic vertebral fracture, a comparison study was performed assessing planar nuclear medicine bone scan to MR imaging. For a single level fracture, the bone scan correctly depicted 96% of the acute fractures. However, as the number of levels increased, the ability of the bone scan to correctly depict the acute fractures decreased precipitously. For three or more levels of activity, the rate of correctly depicting an acute fracture was only 36%. The number and distribution of lesions seen on a bone scan may be helpful in predicting a benign versus malignant process, but it is often not diagnostic by itself (Fig. 8). Positron emission tomography (PET) may be helpful in distinguishing a benign from malignant vertebral fracture. In a recent study comparing MR imaging with PET/CT using a standard uptake value maximum of 4.25, the sensitivity and specificity for detecting a malignant process was 64% and 83% for MR imaging and 85% and 71% for PET/CT, respectively.

**SPINE: PARS INTERARTICULARIS**

Pars interarticularis stress fractures, or isthmic spondylolysis (from the Greek *isthmic* [narrow], *spondylos* [vertebra], and *lysis* [defect]), are located between adjacent facet joints, where the pedicle, lamina, and facet joints coalesce. In a 45-year prospective study of 500 elementary school children using radiographs, the prevalence of pars interarticularis defects at 6 years of age...
was 4.4%, which increased to 6% at adulthood with a male/female ratio of 2:1. Of the pars inter-articularis defects, 73% were bilateral, and of these all occurred at the L5/S1 level. All of the initial 500 children were asymptomatic at the start of the study; by the end of the study, their functional disability scores as measured by the Short Form (36) Health Survey were no different from the general population.

This study suggests that most spondylolytic defects are not symptomatic. In a more recent Japanese CT study of 2000 patients between the ages of 20 and 29 years, the prevalence in the general population was 5.9% with a male/female ratio of 2:1. Of these patients, 90.3% occurred at L5; 5.6% at L4; and 3.2% at L3. These studied populations are distinct from an athletic population, especially elite athletes. In an Italian retrospective review of 3505 athletes with low back pain, 13.5% of athletes had spondylolysis and 81% occurred at the L5/S1 level. Furthermore, the incidence between different sports varies, with a higher occurrence in sports that include axial loading in extension. Another Italian study found 390 cases of lumbar spondylolysis in 3132 athletes with the highest percentages occurring in diving (43%), wrestling (30%), and weight lifting (23%). In yet another study of the Japanese population, the incidence of lumbar spondylolysis was significantly higher in rugby and judo players, with an incidence of 20%, and higher still in soccer and baseball players, with an incidence of 30%.

Spondylolysis is not limited to the lumbar spine but is rare in other spine segments. There have been approximately 100 cases of cervical spondylolysis reported in the literature without a clear, agreed compression fractures should include. Forsberg and colleagues described common imaging findings in a series of 12 patients. These findings include (1) a well-marginated cleft between the facets, (2) a triangular configuration of the pillar fragments on either side of the spondylolytic defect, (3) posterior displacement of the dorsal triangular pillar fragment, (4) hypoplasia of the ipsilateral pedicle, (5) spinal dysraphism at the involved level, and (6) compensatory hyperplasia or hypoplasia of the ipsilateral articular pillars at the level above or below the defect. Awareness of cervical spondylolysis is important to differentiate these findings from an acute fracture; these patients are also at an increased risk of developing neurologic compromise after relatively minor trauma.

The etiology of spondylolysis remains controversial, but it is generally accepted that spondylolysis is multifactorial, with a combination of repetitive microtrauma related to flexion, extension, and rotation superimposed on congenital anatomic variations. In an anatomic study in 1951, Roche and Rowe reported a varied incidence of spondylolysis among races and sex: White men, 6.4%; African American men, 2.8%; White women, 2.3%; African American women, 1.1%. This study supports a genetic component in the etiology of
spondylolysis. Ward and colleagues found that individuals with L5 spondylolysis had an inadequate increase in the transverse lumbar interfacet distance progressing caudally from L4 to S1 when compared with normal control individuals. The normal increase of the transverse interfacet distance progressing caudally in the lower lumbar spine allows the adjacent articular processes to slide by one another without exerting excessive pressure on the intervening pars interarticularis. With the reduction of transverse interfacet distance progressing caudally, the inferior articular process of L4 and the superior articular process of S1 contact the same cross-section of the L5 pars interarticularis by a pinching mechanism first described by Capener in 1931. These forces lead to bony resorption and weakening of the pars interarticularis. Ward and colleagues concluded that these individuals were at higher risk of developing and maintaining a spondylolytic defect. Another contributing anatomic factor was described by Masharawi and colleagues, who studied 115 cadaveric skeletons with L5 spondylolysis compared with 120 controls. These investigators found that greater degrees of coronal orientation, tropism, and asymmetry of the lower lumber facets was strongly associated with spondylolysis. They postulated that sagittally oriented facets allow for facilitated flexion and extension, whereas the more coronally oriented facets subject more force on the pars interarticularis as a result of increased surface area contact by the opposing articular processes.

The imaging evaluation of spondylolysis may include radiographs, nuclear medicine imaging, CT, and MR imaging. Each modality has potential benefits and pitfalls that need to be considered when interpreting these images.

Radiographs

Radiographs are often obtained in the initial workup of low back pain related to spondylolysis. Common projections include AP, lateral, collimated lateral, and 45° oblique images. A displaced pars interarticularis defect can be seen on lateral views as a linear lucency with irregular or rounded margins, depending on the age of the defect. These fractures can also be seen on the 45° oblique views as a lucency traversing the neck of the Scotty dog likened to a collar (Fig. 11). One study consisting of 56 patients detected spondylolytic defects using a series of 6 radiographs including an AP, 30° up-angled AP, lateral, collimated...
lateral, and two 45° oblique views.\textsuperscript{33} This study found that 84% of the defects were detected on the collimated lateral view versus 77% detected on the 45° oblique views.\textsuperscript{33} The oblique views have been considered to be important in the detection of the spondylolytic defects; however, in a CT study, the spondylolytic fracture plane was discovered to be oriented closer to the coronal plane rather than the 45° oblique plane.\textsuperscript{34} This finding explains the higher sensitivity of detecting the spondylolytic defect with the collimated lateral view because it is more tangential to the radiograph beam (\textbf{Fig. 12}).\textsuperscript{33,34} If a collimated lateral radiograph has already been obtained and a spondylolytic defect cannot be detected and is still suspected, oblique images only increase the radiation dose and do not necessarily offer greater diagnostic sensitivity. In this setting of clinical suspicion and negative AP and lateral radiographs, advancing imaging should be used, as discussed later.

Secondary radiographic signs of spondylolysis include lateral deviation of the spinous process, unilateral pedicle sclerosis in cases of unilateral pars interarticularis defects, and spinal dysraphism. Isolated lateral deviation and rotation of a spinous process toward the shorter lamina can occur in cases in which there is a unilateral defect or asymmetric bilateral defect.\textsuperscript{35} The more distracted pars interarticularis defect is the more lengthened side. In cases of unilateral pars interarticularis defects, sclerosis and hypertrophy of the contralateral pedicle and neural arch have been described and attributed to a compensatory stress reaction (\textbf{Fig. 13}).\textsuperscript{36,37} In the Japanese CT study of 2000 patients discussed earlier, spondylolysis was
found to be significantly greater in patients with spinal dysraphism as shown by an odds ratio of 3.7 (Fig. 14). If a suspected spondylolytic defect cannot be detected on radiographs using primary and secondary signs, more advanced imaging techniques may be required.

Spondylolisthesis refers to the degree of anterior translation of the vertebral body with spondylolytic defects in relation to the vertebral body below and was originally classified by Meyerding. The degree of spondylolisthesis is graded from I to V based on the percentage of anterior translation: grade I 0% to 25%; grade II 26% to 50%; grade III 51% to 75%; grade IV 76% to 100%; grade V >100% (spondyloptosis [falling off]) (Fig. 15). Most isthmic spondylolistheses are grade I. A trapezoidal appearance of L5 with a dome-shaped superior endplate of S1 can be seen with chronic spondylolysis with spondylolisthesis.

A measure of motion and thus instability from the pars interarticularis defects can be obtained from flexion and extension radiographs. Although it has been extensively studied, absolute values to distinguish abnormal from normal motion are difficult to ascertain. Some investigators infer instability with sagittal rotation of more than 10° (Fig. 16) and sagittal translation of more than 4 mm on flexion-extension radiographs.

**CT**

With the recent advances in multidetector CT, high-resolution, thin-section images can be rapidly obtained with isotropic voxels ideal for multiplanar two-dimensional reformations. In current clinical practice, CT provides the highest spatial resolution in characterizing a known or suspected spondylolytic fracture. Furthermore, CT is more sensitive than radiographs for identifying the primary and secondary radiographic findings, especially the sclerosis and hypertrophy of the contralateral pedicle and neural arch in unilateral spondylolysis (Fig. 17). This factor can be especially helpful in the diagnosis of osteoid osteoma (often in the differential diagnosis with unilateral spondylolysis) by confirming the presence of a nidus and the absence of a contralateral spondylolysis, which are unlikely to coexist (Fig. 18).

CT has been shown to be best at evaluating the size and extent of the fracture and is the best modality for fracture healing follow-up. The reformed sagittal plane and a plane parallel to the long axis of the articular pillar (also referred to as the reverse gantry technique) better depicts the spondylolytic defect distinct from the nearby facet joint. Fracture progression occurs from the inferior or inferomedial aspect of the pars interarticularis and propagates superiorly or superolaterally, whereas healing occurs in a reverse direction. Fujii and colleagues used CT to study the effect of prognostic variables in the healing of pars interarticularis defects with conservative measures, including a lumbar corset. These investigators found that the stage of the fracture at diagnosis was one of the predominant factors in predicting union. Three fracture stages were established: early, progressive, and terminal. The early stage was defined as a narrow fissure through the pars with sharp margins. The progressive stage was a fissure that was still narrow but had slightly rounded margins. The terminal stage was a wide defect with rounded margins and sclerosis. A significantly greater proportion of defects achieved union at the early stage compared with the progressive and terminal stages. None achieved union at the terminal stage.

**Nuclear Medicine Imaging**

Whereas radiographs and CT may identify pars interarticularis defects, nuclear medicine imaging can provide information regarding metabolic activity, which can be inferred as necessary for the pars defect to be a pain generator. Planar bone scintigraphy and single-photon emission CT (SPECT) have been shown to identify symptomatic patients and sites of spondylolysis in patients with radiographic findings of spondylolysis. SPECT imaging provides better sensitivity than planar bone scintigraphy by improved contrast and anatomic localization without increased radiation (Fig. 20).
examination by itself cannot reliably distinguish a pars interarticularis defect from active facet synovitis, or in the unilateral cases, from a neoplastic process such as an osteoid osteoma, and infection. Bellah and colleagues\textsuperscript{47} stated that a negative SPECT examination virtually excludes a pars interarticularis defect as a etiology for back pain. In a more recent paper by Gregory and colleagues,\textsuperscript{48} a negative SPECT examination translated into an 84.2% chance of not having spondylolysis or a 15.8% chance of having chronic pars defects that are unlikely to be pain generators. Gregory and colleagues assessed the diagnostic value of combining SPECT with CT in the

---

**Fig. 15.** Modified Meyerding classification of spondylolisthesis: grade I 0% to 25%; grade II 26% to 50%; grade III 51% to 75%; grade IV 76% to 100%; grade V greater than 100% (spondyloptosis [falling off]). (Courtesy of Mayo Clinic, Rochester, Minnesota; with permission.)

**Fig. 16.** L5 pars interarticularis instability with flexion (A) and extension (B) radiographs as measured by a sagittal rotation of 12°. Note the distraction of the pars defect in flexion. There is no sagittal translation with flexion and extension.
evaluation of spondylolysis. They described 4 categories of patients: group A, (+) SPECT and (+) CT findings for spondylolysis; group B, (+) SPECT and (–) CT findings for spondylolysis/C6 sclerosis or the pars; group C, (–) SPECT and (+) CT findings for spondylolysis; and group D, (–) SPECT and (–) CT findings for spondylolysis.

Group A and B patients were considered to have a healing potential. Group B patients were deemed to have a stress reaction, which could lead to a stress fracture without activity modification. Group C patients were considered to have chronic defects with no healing potential using conservative measures. Group D patients were generally found or considered to have an alternate pain generator other than a pars interarticularis defect. For this last group, the investigators recommended MR imaging for further evaluation. Of these group D patients who went on to have an MR imaging examination, 50% were diagnosed with discogenic pain as the etiology of their back pain.43,50

MR imaging offers the distinct advantage of no ionizing radiation, which is of great importance in the relatively young population in whom spondylolysis occurs. High-resolution multiplanar techniques have been used to accurately identify pars interarticularis defects.43,50 These sequences include oblique axial reverse gantry angled and sagittal T1-weighted images and STIR images, as well as sagittal three-dimensional spoiled gradient echo sequences.43,50 To stratify the stress injuries, an MR imaging classification was developed by Hollenberg and colleagues (Table 1).51

This classification has been shown to have high intraobserver and interobserver reliability, as well as correlating well with CT and SPECT.53,50,51 Grade 0 (normal) was assigned to the patients without signal abnormality of the pars interarticularis; grade 1 (stress reaction) denoted patients with T2 hyperintensity of the pars interarticularis with or without signal changes in the adjacent pedicle or articular process; grade 2 (incomplete fracture) identified the patients with T2 hyperintensity and thinning, fragmentation, or irregularity of the pars interarticularis visible on T1-weighted or T2-weighted images; grade 3 (complete active fracture) involved a visible complete unilateral or bilateral spondylolysis with associated abnormal T2 signal (Fig. 21); grade 4 (complete chronic fracture) was reserved for the cases of complete spondylolysis without abnormal T2 signal.51

In a study by Campbell and colleagues,50 the aim was to evaluate whether MR imaging correlates with CT and SPECT imaging for the diagnosis of juvenile spondylolysis, and to determine whether MR imaging can be used as an exclusive image modality. These investigators found excellent agreement (κ >0.77) between MR imaging and SPECT. This study implies that MR imaging, with the addition of the oblique and STIR sequences, can replace SPECT in evaluating for metabolically active spondylolytic lesions. Furthermore, when comparing MR imaging with the combined CT and SPECT data, which was considered the gold standard, MR imaging correctly identified 73% of the pars defects but also showed some form of secondary signal change or morphologic abnormality in 98% of
Fig. 18. 14-year-old boy with an osteoid osteoma. (A) AP radiograph of the lumbar spine reveals a levo-scoliosis and L5 spinal dysraphism but no other findings to suggest an osteoid osteoma or spondylolysis. (B) Maximum intensity projection of a nuclear medicine SPECT study shows intense radiotracer activity about the right L4 pedicle, which is nonspecific and can be seen with either an osteoid osteoma or spondylolysis. (C, D) T2-weighted MR imaging confirms the presence of a low-signal-intensity nidus (white arrows) within the superior articular process of the right L4 vertebrae with surrounding reactive bone marrow edema. There are no findings for spondylolysis. (E) CT better depicts the relatively lower attenuation nidus (arrow) and absence of a pars defect, all consistent with an osteoid osteoma, which was eventually surgically excised. (Courtesy of Doris Wenger, MD.)

Fig. 19. Pars interarticularis fracture stages (dashed circles). (A) Early stage: narrow fissure through the pars with sharp margins. (B) Progressive stage: fissure that was still narrow but had slightly rounded margins. (C) Terminal stage: wide defect with rounded margins and sclerosis. (Courtesy of Timothy Maus, MD.)
the spondylolytic cases. The use of secondary signs to identify spondylolysis was described for radiographs and CT earlier and can be equally useful in MR imaging. Ulmer and colleagues described secondary findings present in 97% of 66 levels of lumbar spondylolyses studied. These findings included a widened sagittal spinal canal diameter (91% of cases), posterior wedging of the vertebral body bearing the defect (48% of cases), and reactive bone marrow edema in one or both of the adjacent pedicles (36% of cases). Another study evaluated 36 pediatric and adolescent patients with 68 pars interarticularis defects using MR imaging and CT. These investigators found that all the pars defects in the early stage on CT showed T2 hyperintensity in the ipsilateral pedicle (Fig. 22). They also found that none of the pars defects in the terminal stage on CT showed T2 hyperintensity in the ipsilateral pedicle. Of the 19 pars defects that showed T2 hyperintensity, 79% went on to heal with conservative management. Of the 10 pars defects that did not show T2 hyperintensity, none went on to heal. These investigators’ conclusion was that T2 hyperintensity in the pedicle adjacent to a pars defect suggests an early diagnosis of spondylolysis and a greater potential for healing with conservative measures. In a prospective study of 15 pediatric and adolescent patients with 22 early spondylyotic defects studied with CT and MR imaging and treated conservatively, most patients had resolution of the T2 hyperintensity at the 3-month follow-up; a longer period was needed for signal resolution in the few patients poorly compliant with therapy. Nearly all the patients went on to heal and were symptom free with the resolution of the T2 hyperintensity. These investigators concluded that follow-up MR

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
<th>MR Imaging Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Normal</td>
<td>Normal bone marrow signal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No cortical disruption</td>
</tr>
<tr>
<td>1</td>
<td>Stress reaction</td>
<td>Bone marrow edema</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No cortical disruption</td>
</tr>
<tr>
<td>2</td>
<td>Incomplete fracture</td>
<td>Bone marrow edema</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Incomplete fracture through the pars interarticularis</td>
</tr>
<tr>
<td>3</td>
<td>Acute complete</td>
<td>Bone marrow edema</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Complete fracture through the pars interarticularis</td>
</tr>
<tr>
<td>4</td>
<td>Chronic complete</td>
<td>No bone marrow edema</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Complete fracture through the pars interarticularis</td>
</tr>
</tbody>
</table>
imaging at 3 months after the initiation of conservative therapy can predict the success of treatment.

Campbell and colleagues noted that the greatest discordance between MR imaging and CT was with grade 2 lesions in which the pars fracture is incomplete and cannot be reliably distinguished from the evolutionary or healing phase across all modalities at a single point in time. This result was supported by Dunn and colleagues, who evaluated grade 2 pars fractures with MR imaging and CT. These investigators concluded that MR imaging is limited in its ability to fully depict the cortical integrity of incomplete fractures of the pars, but the presence of marrow edema on the fluid-sensitive sequences (STIR and T2-weighted with fat saturation) is a useful means of detecting acute spondylolysis. Of the CT-confirmed incomplete fractures, 77% showed a break in the inferomedial cortex of the pars interarticularis on MR imaging, whereas 92% showed reactive bone marrow edema about the pars. Another more recent study by Ganiyusufoglu and colleagues comparing the diagnostic accuracy of MR imaging with CT had similar results. These investigators found that MR imaging has a comparable diagnostic accuracy to CT in detecting complete fractures with or without accompanying

Fig. 21. Sagittal T2-weighted MR imaging images of complete left (A) and right (B) L5 pars interarticularis fractures (dashed white circles) containing tiny fluid signal with mild surrounding bone marrow edema, all compatible with MR imaging grade 3 spondylolysis. (Courtesy of Patrick Eiken, MD.)

Fig. 22. (A) Sagittal STIR MR imaging in a 15-year-old girl with 9 months of right low back pain. There is increased T2 signal in the right L4 pedicle (dashed white circle). (B) Corresponding sagittal CT shows an early-stage right L4 pars interarticularis fracture with mild surrounding sclerosis (dashed white circle). These combined findings are compatible with an early spondylolytic fracture that has a good chance of healing with conservative measures. (Courtesy of Timothy Maus, MD.)
marrow edema and incomplete fractures with accompanying bone marrow edema, especially at the lower lumbar levels. The sensitivity of MR imaging in the detection of incomplete fractures was 75%, consistent with the findings presented by Ganiyusufoglu and colleagues.55 Campbell and colleagues\textsuperscript{50} concluded that MR imaging can be used as an effective and reliable first-line image modality for diagnosis of juvenile spondylolysis. Limited CT was recommended as an additional complementary examination in selected cases as a baseline for healing assessment, and for evaluation of indeterminate cases.

There are several other potential imaging pitfalls that one must be aware of when evaluating spondylolysis with MR imaging. Singh and colleagues\textsuperscript{56} evaluated contiguous axial images compared with disc space targeted angled axial images and found a 50% decrease in detection of pars defects using the disc space targeted angled axial images compared with the contiguous axial images. The finding was not statistically significant because of the sample size. However, these investigators further observed that the disc space targeted angled axial images nearly excluded the pars interarticularis region. Furthermore, if a spondylolytic fracture was present, it was nearly parallel to the plane of the disc space targeted angled axial images, making detection even more difficult.\textsuperscript{56} Potential false-positive findings of a spondylolytic defect on MR imaging may be the result of partial volume averaging of a marginal osteophyte from the adjacent superior facet, partial facetectomy, and sclerosis of the pars related to an osteoblastic metastasis.\textsuperscript{57}

MR imaging can be used to evaluate the disc and nerve roots in cases of spondylolisthesis with and without spondylolisthesis as pain generators (Fig. 23). The lack of a structural connection between the anterior and posterior columns places significant shear stress on the intervertebral disc; it may develop internal disc disruption and be the etiology of axial pain (discogenic pain). Subsequent loss of disc space height and possible anterior translation of the vertebral body causes foraminal narrowing in a characteristic forward-leaning S shape, manifest clinically as radicular pain or radiculopathy. In cases in which no pars interarticularis defects are identified, MR imaging can potentially identify other causes of pain that may be difficult or impossible to evaluate with other modalities.

**SPINE: PEDICLE**

Pedicle stress fractures are less common than vertebral fractures and fractures of the pars interarticularis, as noted in a recent case report and literature review.\textsuperscript{58} Aside from pedicle fractures related to trauma and previous surgery, the prevalence of pedicular stress fractures is difficult to ascertain. A study evaluating T2 hyperintensity of the pedicle on MR imaging and its relationship to symptoms in patients without acute trauma reported a pedicle fracture incidence of 7.6%.\textsuperscript{59} When this subset of patients displaying T2 hyperintensity of the pedicle

---

**Fig. 23.** Bilateral L5 spondylolysis with spondylolisthesis contributing to radiculopathy. (A) T1-weighted MR imaging showing marked L5 neuroforaminal narrowing with near complete obliteration of the epidural fat about the L5 nerve root (white arrow). Irregular low-signal intensity across the pars defect (dashed white oval). (B) T2-weighted MR imaging without bone marrow edema about the pars defect (dashed white oval) consistent with a chronic process. (Courtesy of Timothy Maus, MD.)
was broken down by age, 71% of the pedicle fractures occurred in patients less than 30 years of age.\textsuperscript{55} These investigators did not report any association with pars interarticularis defects; however, it has been shown that pedicular stress fractures may be highly prevalent in cases of unilateral spondylolysis (Fig. 24).\textsuperscript{60} In a study of 13 athletic patients younger than 20 years with unilateral spondylolysis diagnosed with MR imaging and CT, 46% showed a contralateral pedicle fracture or a chronic pedicle stress reaction in the form of sclerosis. None of the patients were in the early stage of spondylolytic fracture as seen on CT; nearly all were in the terminal stage.\textsuperscript{60} The investigators also performed a finite element analysis of the stress imparted by a unilateral pars defect on the contralateral neural arch and found an increase in stress with all 6 tested lumbar motions, with the highest occurring in axial rotation.\textsuperscript{60} The finite element analysis and the clinical findings of a unilateral pars defect support that cumulative stresses across the contralateral neural arch can lead to pedicle injuries and as the stage of the spondylolytic defect progresses so does the contralateral stress.\textsuperscript{60}

**Imaging**

Imaging of pedicle stress fractures may be similar to imaging pars interarticularis defects. Radiographs are relatively insensitive in detecting pedicle stress fractures, as seen with vertebral fractures and pars defects.\textsuperscript{13,33,34} Bone scintigraphy with SPECT was favored for initial assessment followed by CT for further evaluation in a 1991 publication.\textsuperscript{61} As detailed earlier, SPECT combined with CT imparts a noteworthy amount of radiation to a relative young population and therefore may not be the best screening examination. MR imaging using standard sequences including T1-weighted and T2-weighted fat-saturated or STIR images may prove to be the best initial examination, because it does not impart ionizing radiation and uses physiologic imaging parameters of edema to identify early findings of a pedicle stress reaction (Fig. 25).\textsuperscript{58} As with spondylolysis, limited CT may be used after MR imaging as an additional complementary examination in selected cases, and as a baseline for following fracture healing. If no pedicle injury is found, MR imaging is best able to identify other pain generators that may be difficult or impossible to evaluate with other modalities.

**SACRUM**

Sacral stress fractures can present as low back pain and the diagnosis can be elusive from both a clinical and imaging standpoint. These stress fractures can be seen in various patient populations. One is the young athlete presenting as a fatigue fracture. The prevalence of sacral fatigue fractures is unknown but this entity is believed to be uncommon and reported most often in female athletes, including distance runners.\textsuperscript{62} Postmenopausal women with osteoporosis are another distinct population who are predisposed to sustaining sacral insufficiency fractures.\textsuperscript{63} As with the younger patient, the prevalence is unknown but has been reported to be 1.8% of women older than 55 years in 1 series.\textsuperscript{64} Sacral insufficiency fractures can also be seen in patients with rheumatoid arthritis, those undergoing corticosteroid treatment, and after pelvic irradiation for gynecologic malignancy.\textsuperscript{65} Sacral stress fractures may be

---

**Fig. 24.** (A) Axial CT scan of a left L5 terminal stage spondylolytic defect (white arrow) in a 29-year-old male athlete with a subacute to chronic contralateral pedicle stress fracture (dashed black circle). Sagittal CT images better showing the left (B) L5 pars defect and the right (C) pedicle fracture (dashed white circle). Incidental note is made of a lumbarized S1 segment. (Courtesy of Timothy Maus, MD.)
imaged with radiographs, nuclear medicine imaging, CT, and MR imaging.

**Radiographs**

When evident on radiographs, sacral stress fractures can be seen as vertically oriented bands of sclerosis involving the ala paralleling the sacroiliac joints.\(^{65}\) Sacral stress fractures can be difficult to appreciate on radiographs because of overlying bowel gas, arterial calcifications, and osteopenia, the latter two generally seen in older populations.\(^{45,66–68}\) In a study comparing MR imaging with CT for the detection of insufficiency fractures, a subset of patients also had radiographs available. Of these patients, only 3.8% of the sacral insufficiency fractures could be detected using radiographs.\(^{69}\)

**Nuclear Medicine Imaging**

Nuclear medicine bone scan can be sensitive in detecting sacral stress fractures. The classic finding of a sacral insufficiency fracture on a nuclear medicine bone scan is the Honda sign (Fig. 26). This sign occurs when the radiotracer activity appears as the letter H, with the vertical components along the sacral ala and the horizontal component crossing the sacral body. When the Honda sign and its variants (missing portions of the H) were identified, the sensitivity and positive predictive value were found to be 96% and 92%, respectively.\(^{70}\) In 63% of these patients, a complete Honda sign was identified, whereas 33% showed variants of the Honda sign. The radiotracer activity can be variable at follow-up and may be present 8 to 10 months after the initial presentation.\(^{63,66}\)

**MR Imaging**

MR imaging can also be used to detect sacral stress fractures, with a reported sensitivity of 100%.\(^{69}\) MR imaging of the sacrum for this indication should include axial and coronal oblique T1-weighted and T2-weighted fat-suppressed or STIR images. The bone marrow edema is evident as increased signal on the T2-weighted and STIR images (Fig. 27), whereas the fracture line may be visible as a linear low-signal intensity following the pattern of the Honda sign or its variants.\(^{69}\) A potential imaging pitfall is when a lumbar spine MRI examination is performed for back pain in patients who have an unsuspected sacral stress fracture. Routine lumbar spine MR imaging does not include all of the sacrum, and coronal oblique

---

**Fig. 25.** T1-weighted (A) and T2-weighted with fat saturation (B) sagittal MR images through the right L5 pedicle (dashed white circle). There is increased T2 signal within the pedicle without a corresponding linear low-signal abnormality, compatible with the clinically concordant stress reaction of the pedicle without fracture.

**Fig. 26.** Nuclear medicine bone scan Honda sign of sacral insufficiency fractures. The radiotracer activity forms the letter H, with the vertical components along the sacral ala and the horizontal component crossing the sacral body.
images of the sacrum are not routinely obtained (Fig. 28). As discussed in the preface to this issue, the imager must know the location and character of the pain syndrome to appropriately image the patient.

**CT**

CT can depict the sclerosis and a fracture line with greater sensitivity than radiographs. MR imaging and CT were compared in the evaluation of

---

Fig. 27. MR imaging of sacral insufficiency fractures. The fractures form vertically oriented bands of decreased T1 (A) and increased T2 signal (B).

Fig. 28. Routine MR imaging examination of the lumbar spine. The rightmost sagittal image suggests a subtle decreased T1 (A) and increased T2 (B) signal abnormality of the sacral ala in a patient with back pain (dashed white ovals). Coronal oblique T1-weighted (C) and T2-weighted fat-saturated (D) sequences were added through the sacrum, which better depicts the new right sacral insufficiency fracture (dashed white ovals). The patient had undergone a sacroplasty of the left sacral ala 2 months previously, accounting for the signal changes in that region.
insufficiency fractures about the pelvis, sacrum, and proximal femur. MR imaging detected 100% of the sacral insufficiency fractures, whereas CT detected only 74.6%. Although MR imaging and scintigraphy are more sensitive than CT in the detection of sacral insufficiency fractures, CT may provide complementary, detailed, high-resolution imaging of the cortical involvement of the fracture as it relates to neural foramina in patients being considered for sacroplasty, because they can be potential areas of cement leakage (Fig. 29).

**PELVIS**

Sacral alar fractures are the most common of the pelvic fractures, but insufficiency fractures may occur at other pelvic sites, including the pubic rami, the pubic bone near the symphysis, and the periacetabular region. These fractures may present as hip or groin pain and may provoke an imaging investigation that begins in the spine. These lesions are also apparent as linear zones of sclerosis which are subtle on radiographs and more evident on CT. These lesions may have a bone marrow edema pattern, possibly accompanied by a low-signal fracture line, on MR imaging. The presence of one insufficiency fracture should provoke careful scrutiny for other such lesions at sites of known predilection.

**SUMMARY**

As with many things in medicine, timely diagnosis is paramount in reducing morbidity from the afflicting condition. This goal is especially challenging in stress fractures of the spine, which can occur in both young and old patients, may be overlooked in the differential diagnosis, and can be difficult to detect without advanced imaging. Appropriate imaging of these conditions is a daunting task and is ever changing with the advances in technology and imaging techniques. As is seen elsewhere in this issue, the imager must be aware of the nature of the pain syndrome and the clinical suspicion to appropriately direct the imaging. Structural changes are difficult to detect until late in the process; early diagnosis depends on physiologic parameters of bone marrow edema or accelerated bone metabolism. Imaging must be undertaken with due regard to cost and radiation exposure, particularly in the adolescent spondylosis population.

**ACKNOWLEDGMENTS**

The author wishes to thank Dr Timothy Maus for his mentorship and sharing his wealth of knowledge including case examples. Also, a special thanks to Mrs Jane Gagnon for her assistance in preparation of this article.

**REFERENCES**


---

Fig. 29. Coronal oblique T1-weighted (A) and STIR (B) MR images of a vertically oriented right sacral ala insufficiency fracture (white arrows). The low-signal-intensity fracture line nears the S1 and S2 sacral neural foramina without definite extension into the foramina. (C) Corresponding coronal oblique CT of the same sacral insufficiency fracture (white arrows) taken immediately before sacroplasty confirms that there is no fracture extension into the sacral foramina, as shown by intact cortical margins.