Imaging of Structural Abnormalities of the Sacrum: The Old Faithful and Newly Emerging Techniques

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Abstract

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The sacrum and sacroiliac joints pose a long-standing challenge for adequate imaging because of their complex anatomical form, oblique orientation, and posterior location in the pelvis, making them subject to superimposition. The sacrum and sacroiliac joints are composed of multiple diverse tissues, further complicating their imaging. Varying imaging techniques are suited to evaluate the sacrum, each with its specific clinical indications, benefits, and drawbacks. New techniques continue to be developed and validated, such as dual-energy computed tomography (CT) and new magnetic resonance imaging (MRI) sequences, for example susceptibility-weighted imaging. Ongoing development of artificial intelligence, such as algorithms allowing reconstruction of MRI-based synthetic CT images, promises even more clinical imaging options.

Sacral imaging poses a challenge because of its complex anatomy and posterior location in the pelvis. In addition, the sacrum and sacroiliac joints (SIJ) are composed of multiple tissues (including cortical and cancellous bone, bone marrow, cartilage, synovium, ligaments, and the thecal sac with neural roots within the sacrum). Each of these different components may lead to a variety of pathologies, such as inflammatory and infectious diseases, fractures, and benign and malignant masses. These various tissues and pathologies are best visualized by different techniques.

We discuss relevant anatomy and anatomical variants. We also review different imaging techniques used for sacral imaging, each with its clinical indications, strengths, and disadvantages, including new and emerging techniques like dual-energy computed tomography (DECT) and artificial intelligence (AI) applications.

Anatomy

The sacrum consists of five vertebrae that fuse into a concave triangular bony structure. It can be divided into three main regions: the left and right ala, lateral to the neuroforamina on each side, and the body that sits between the foramina.[1] The body withholds part of the thecal sac and the sacral nerve roots before they exit through the sacral foramina and form the sacral plexus.

The sacrum is the most posterior part of the pelvic ring and articulates with both iliac bones through the SIJ. The ventral-inferior portion of these oblique-oriented joints consists of a synovial joint; the dorsal-superior portion is a syndesmosis made up of the interosseous sacroiliac ligament. The sacrum is also a part of the axial skeleton, acting as an extension of the vertebral column. S1 articulates with the lumbar spine through an intervertebral disk and bilateral facet joints. Various ligaments support these joints and connect the bones.

Anatomical Variants and Their Pitfalls

A wide range of variants has been described regarding the SIJ.[2–6] They are present in 32 to 52% of the general population

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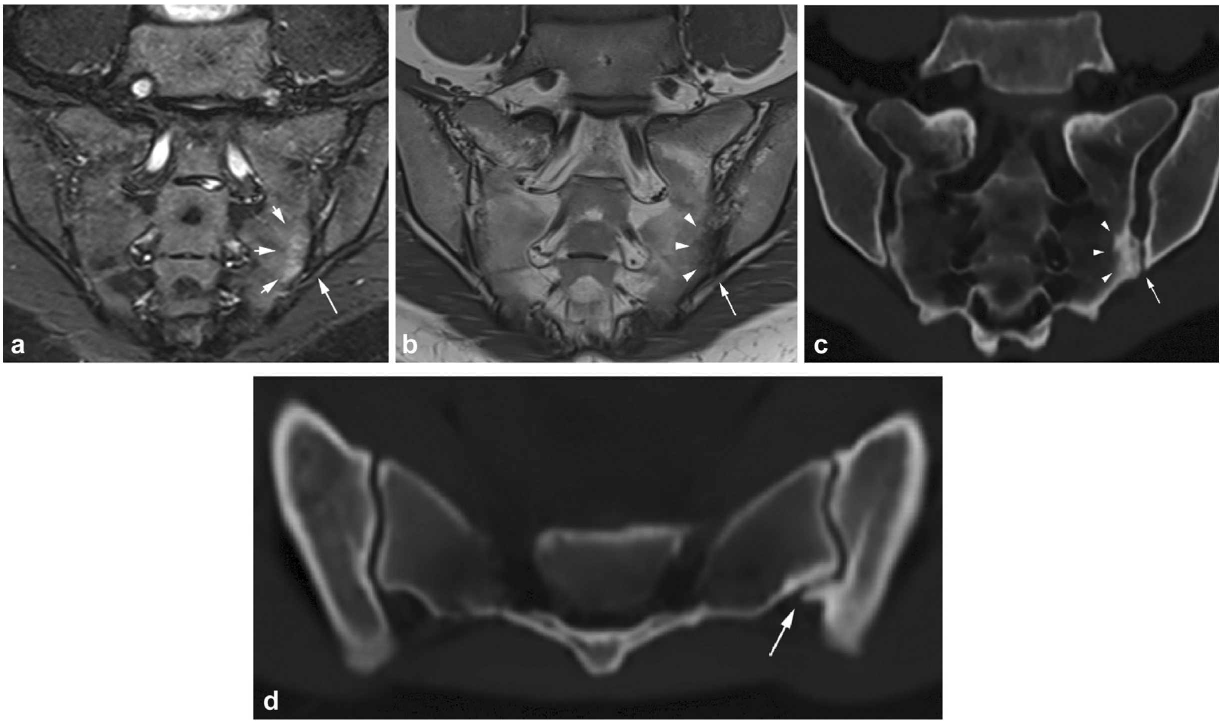

Fig. 1 A 31-year-old woman with left-sided sacroiliac pain. (**a**) Semicoronal short tau inversion recovery, (**b**) semicoronal T1, (**c**) semicoronal and (**d**) axial reconstructed synthetic computed tomography images based on magnetic resonance imaging demonstrate an accessory sacroiliac joint on the left (long arrows), with degenerative alterations consisting of adjacent edema (short arrows) and sclerosis (arrowheads).

and include the accessory SIJ, iliosacral complex, bipartite iliac bony plate, crescent iliac bony plate, semicircular defect, unfused ossification center, isolated synostosis, and dysmorphic changes.[2–6] Their etiology remains debated. Congenital and genetic factors have been suggested, as well as acquired forms (related to mechanical stress).[2–4] A high incidence of degenerative changes in the accessory SIJ has been described, and these patients frequently reported mild low back pain, which may indicate its clinical relevance (►**Fig. 1**).[3] Sclerotic, fatty, and edematous changes in patients with accessory SIJ have been demonstrated and considered as mechanical changes, and they should not be mistaken for inflammatory sacroiliitis.[4] Recognizing these anatomical variants is mandatory because they are frequently associated with structural or edematous changes that can simulate pathology.[2–4]

Multiple types of transitional vertebrae exist, with a reported prevalence of 4 to 30%,[7] ranging from sacralization and fusion of L5 with the sacrum at one end of the spectrum and complete lumbarization of S1 at the other end. An important factor in these variants is the enlarged transverse process of L5 that can be fused to the sacrum to a varying degree, from pseudoarticulation to complete osseous fusion.[8] The most commonly used classification is the Castellvi radiographic classification.[9] It can be difficult to identify L5 and S1 correctly, especially if only part of the spine is imaged (in which case counting the ribs as a point of reference is excluded). The iliolumbar ligament origins at the transverse process of L5 in 96% of patients, but is not always visible on magnetic resonance imaging (MRI) (►**Fig. 2**).[10] The clinical relevance and potential association of these lumbosacral transitional variants with low back pain (the so-called Bertolotti syndrome) remains controversial. Some studies found an association with degenerative changes.[8,11] Without a doubt, lumbosacral transitional variants are a significant risk factor for spine surgery at the wrong level.[7,12] Understanding these variants and careful examination and description of the patient's anatomy is therefore fundamental.[12]

Imaging Techniques

Radiography

Radiography often remains the first step in an imaging workup of the sacrum because of its wide availability, low cost, and ease of use. The obtained images typically includes anteroposterior and lateral views. Some modifications have been proposed, especially to better depict the SIJ (e.g., posteroanterior and oblique views), but none was found to be superior.[13–16] Although it is less sensitive than computed tomography (CT) and MRI for detecting early arthritic changes, radiography is the most cost-effective technique for depicting structural bony changes.[13,14]

Radiographic clues for sacral fractures are often subtle, and interpretation can be challenging, but fracture detection is important given its association with traumatic neuropathy and/or radiculopathy (►**Fig. 3**).[1] Sacral fractures rarely occur isolated; they are reported in 10% up to 45% of patients with pelvic fractures.[17] Therefore, a sacral fracture should always be suspected when anterior pelvic ring disruption is present.[1] Sensitivity, however, is rather low, reported as low as 10.5% in a study of 233 patients $\geq$ 75 years of age who

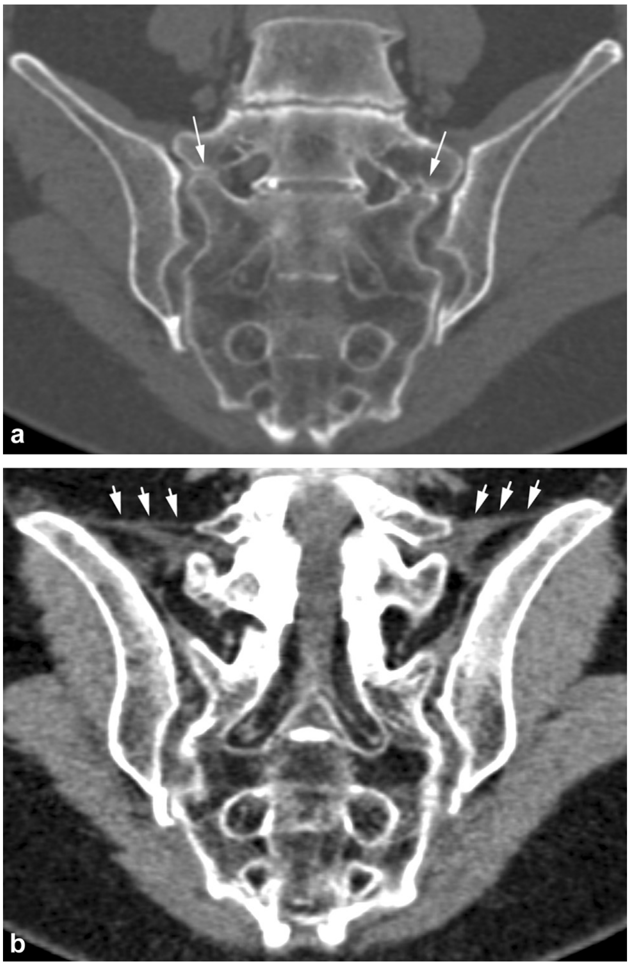

Fig. 2 Semicoronal computed tomography images of the lumbosacral spine in (**a**) bone and (**b**) (slightly more posteriorly) soft tissue. A 68-year-old woman with lumbarization of S1 and additional facet joints S1–S2 (long arrows), with signs of degeneration on the left. The iliolumbar ligament arises from the transverse process of L5 on both sides (short arrows). Also note the degenerative changes at the caudal part of both sacroiliac joints.

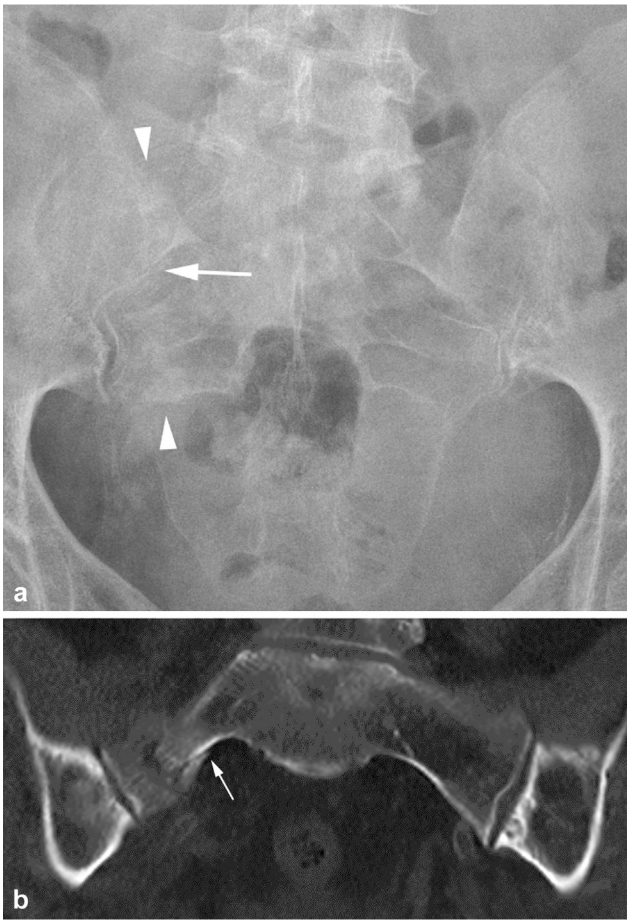

Fig. 3 (**a**) Radiograph and (**b**) coronal computed tomography (CT) image of a 58-year-old woman who was involved in a motor vehicle collision. Subtle disruption of the S1 arcuate line (arrow) is depicted as a sign of vertical fracture involving a foramen. The vertical fracture is further noticed as a hazy dense vertical zone over the right sacral wing on conventional radiograph (between arrowheads), consistent with disrupted, partially impacted, and superimposed bone trabeculae. On CT, the fracture can be better visualized.

experienced blunt pelvic trauma; consequently, CT should be the standard of care in symptomatic patients, in low- and high-energy trauma equally.[18]

Low sensitivity and specificity are obviously major disadvantages of radiography in detecting any anomaly, given the superimposition of the complex structures of the sacrum and SIJ. Another drawback is the use of harmful ionizing radiation.

Ultrasonography

Limited indications exist for ultrasonographic (US) imaging of the sacrum and SIJ in adults, given its inability to examine bony structures except for the superficial cortical lining. However, it can be used in infants up to 3 or 4 months old because the posterior elements of the spine are cartilaginous and not yet ossified, as opposed to older children and adults.[19,20] Because US is easily accessible, safe, does not require sedation, and can be performed bedside, it is well suited as a first step in the imaging work-up of patients with suspected anomalies of the lumbosacral spine, such as complicated sacral dimple, soft tissue mass, and screening in infants with multiple other congenital anomalies.[19] US is often performed in newborns with suspected or prenatally diagnosed sacrococcygeal teratoma. These germ cell tumors are mostly benign, but malignant degeneration can occur. Solid hyperechoic components, hemorrhage and/or necrosis, and sacral bony destruction are more likely to be found in malignant teratomas. However, in these cases, MRI remains the modality of choice.[21] An inherent drawback of US is its known operator dependency.

Computed Tomography

CT provides an excellent anatomical overview and allows for multiplanar and three-dimensional (3D) reconstruction, which is particularly useful in the evaluation of the curved semicoronal positioned sacrum. CT images have great soft tissue–bone contrast, allowing visualization of the entire cortex and detailed analysis of fractures, structural damage to the SIJ in spondylarthritis (erosions, subchondral sclerosis, syndesmophytes, and ankylosis), and delineation of osseous tumors.[1,13,22]

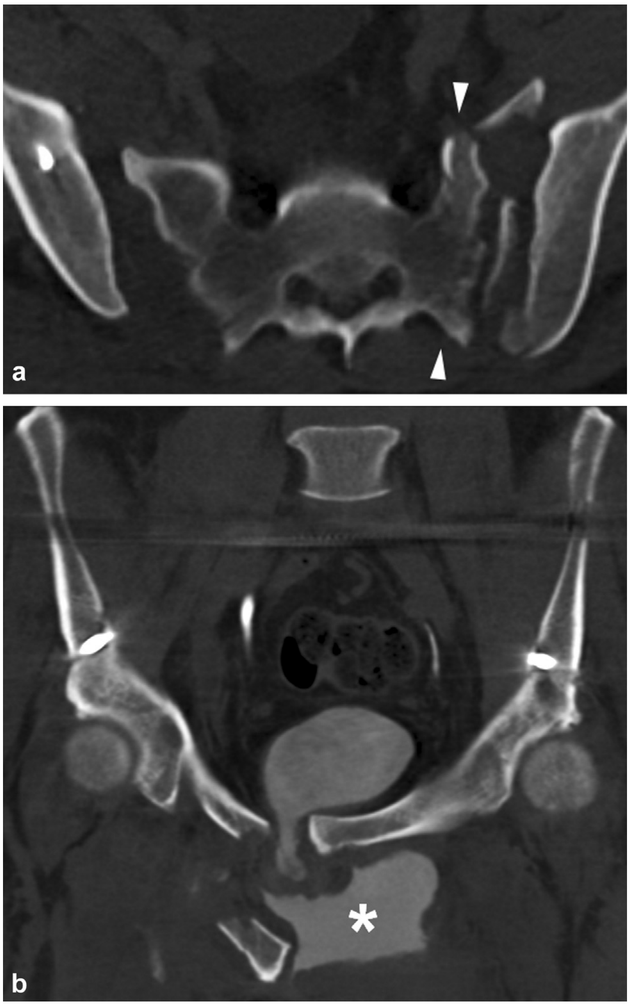

Fig. 4 A 47-year-old man with a highly unstable pelvic ring fracture after a high-energy local impact, temporarily fixated by an external fixation device. (**a**) Axial and (**b**) coronal computed tomography reformations demonstrate diastasis of both sacroiliac joints, indicating ligamentous rupture, a vertical fracture of the left sacral ala (between arrowheads), and fracture-dislocation of the pubic symphysis. There is an associated extraperitoneal rupture of the bladder, with leakage of contrast-enriched urine into the surrounding soft tissues (asterisk). Note the artifacts on the coronal image, caused by the metal external fixation device.

Given the wide availability and short examination time, CT is ideally suited for the evaluation of trauma patients. CT has the advantage of detecting associated soft tissue injury (e.g., hematoma or bladder rupture) (►**Fig. 4**). Different types of sacral fractures may occur; most are longitudinal and/or transverse fractures, and both may cause mechanical (i.e., stability) and neurologic issues. The combination of transverse and longitudinal fractures can lead to spinopelvic dissociation with complete separation of the spine from the pelvis, representing a highly unstable situation.[1] However, this is not the case for the classically H-shaped insufficiency fracture; most of these are regarded as stable.[23]

Because the radiation dose of CT is considerably higher than in radiography, this technique is less suited for children, women of childbearing age, and pregnant women.[24]

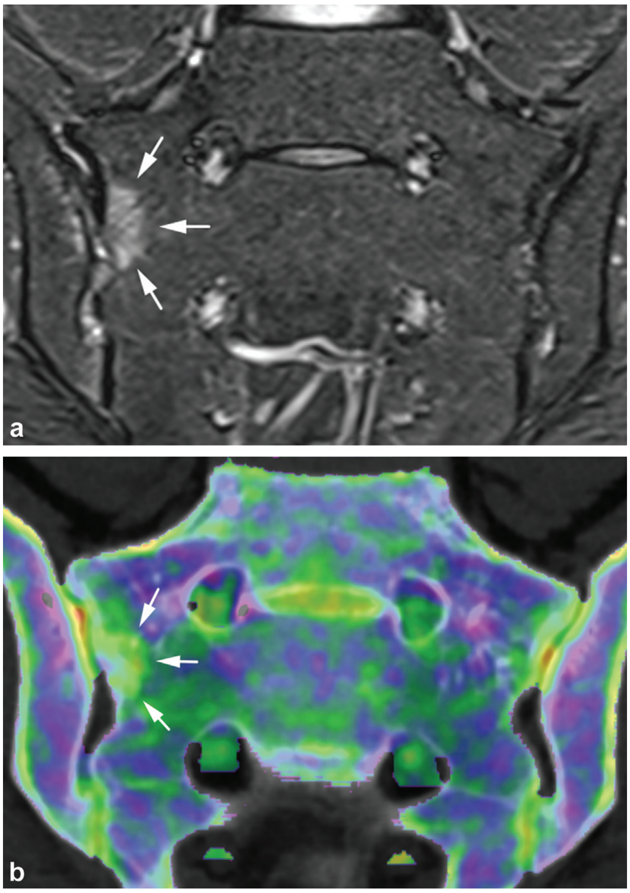

Fig. 5 A 28-year-old woman with active sacroiliitis. (**a**) Semicoronal short tau inversion recovery and (**b**) virtual non-calcium images from a magnetic resonance imaging and a dual-energy computed tomography examination, respectively, both show sharply demarcated focal bone marrow edema along the right sacroiliac joint (arrows).

Dual-energy Computed Tomography

In DECT, two data sets of images are simultaneously acquired at different energy levels (e.g., 80 and 140 kV), allowing differentiation between elements with high atomic numbers, such as iodine and calcium, and elements with low atomic numbers, such as hydrogen and carbon.[25,26] Virtual non-calcium (VNCa) images can be rendered by subtracting calcium from cancellous bone, allowing visualization of bone marrow edema, which is often displayed in color-coded maps.[25] Because bone marrow edema is an essential feature of fractures, this technique improves the rate of fracture detection and outperforms conventional CT with high sensitivity (85–100%) and specificity (95–100%).[27,28] This technique is especially useful in fractures with little or no cortical displacement. Moreover, using DECT, inflammatory bone marrow edema can also be detected in the sacrum with high specificity in patients with sacroiliitis (►**Fig. 5**).[29] Other applications include metal artifact reduction and detection of urate cristal depositions in the SIJ of patients with gout.[25] Counterintuitively, the radiation dose of DECT is comparable with conventional CT because it is divided between both energy levels.[30]

Nuclear Imaging

Bone scintigraphy or bone scan uses technetium-labeled diphosphonates to depict osteoblastic activity; hence areas

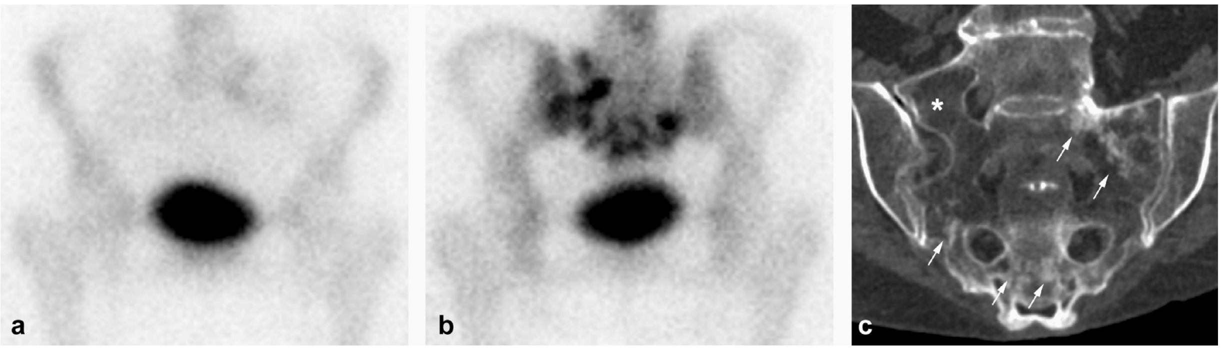

Fig. 6 An 81-year-old woman presenting with pain on the left sacroiliac joint (SIJ) after a low-energetic fall. Conventional radiograph and computed tomography (CT) (not shown) demonstrated degenerative changes of both hips and SIJ but were otherwise normal. (**a**) Anterior and (**b**) posterior bone scintigraphy, obtained 2 months later because of persistent pain, revealed foci of increased activity in the sacrum (more on the left side). (**c**) Semicoronal CT image, acquired 6 months after the initial fall, clearly demonstrates sclerosis (arrows) in the now healing fracture sites. Incidental finding of sacralization of L5 on the right side (asterisk), Castellvi type 3a.

of high bone activity and turnover are highlighted. Single-photon emission computed tomography (SPECT) can additionally be obtained, to acquire 3D distribution of the injected radionuclide, providing more contrast and better spatial resolution. To further augment spatial resolution, CT can be added. Indications include detection of (radiographically occult) fractures such as stress or insufficiency fractures, osteomyelitis, and skeletal metastases.[31,32]

Bone scintigraphy is one of the most sensitive examinations for the detection of sacral insufficiency fractures, with a sensitivity up to 96%. Various patterns of these fractures have been described. Most typically, although only present in up to 40% of patients, is the H-pattern (the so-called Honda sign).[23] SPECT-CT has a higher sensitivity than conventional CT in detecting posterior pelvic ring fractures because these fractures are often nondisplaced and almost invisible on CT (►**Fig. 6**).[32]

Bone scintigraphy is also very sensitive for detecting new bone formation in any type of musculoskeletal inflammation, but its lack of anatomical details and its inability to depict soft tissue inflammation and abscess formation is an important disadvantage.[33–35] The radiation dose is another disadvantage, but the major drawback of bone scintigraphy is that it is not specific and often does not allow further differentiation of a detected abnormality. Adding CT images often helps in the differential diagnosis.

Magnetic Resonance Imaging

MRI offers excellent tissue contrast and differentiation, without the use of ionizing radiation. It allows multiplanar acquisitions with equally high spatial resolution and anatomical detail. It is therefore highly appropriate in the imaging of sacroiliitis (both infectious and inflammatory) and tumoral lesions, and in the detection of bone marrow edema in various conditions.[14,22] Disadvantages of MRI are the high cost, long acquisition time, high sensitivity to movement, and multiple contraindications including claustrophobia and some metallic implants and foreign bodies.

MRI has a higher sensitivity than CT in the detection of acute sacral fractures. This is particularly true in older adult patients with reduced bone density because detection of nondisplaced fractures on CT is hampered in osteoporotic patients in comparison with younger patients.[36,37] Fluid-sensitive sequences draw the attention toward bone marrow edema surrounding the fracture, and the fractures stand out as hypointense lines against hyperintense fat bone marrow on T1-weighted images.

Furthermore, MRI remains the imaging modality of choice in patients with suspected sacroiliitis in spondyloarthritis (SpA) because it allows for early detection due to its high sensitivity for active inflammatory lesions on fluid-sensitive sequences.[13,14] Other active inflammatory lesions include enthesitis, capsulitis, fluid in the joint space, and synovitis. Of note, intravenous injection of gadolinium is needed for detecting the latter. Structural bone lesions of sacroiliitis in SpA can be depicted as well on MRI; these are classically assessed on T1-weighted images. These lesions typically consist of erosions and ankylosis (both highly specific for SpA), as well as periarticular fat metaplasia, subchondral sclerosis, and backfill (which is high T1 signal intensity in the joint space, frequently in an erosion at the joint surface) (►**Fig. 7**).[13,38,39]

When sacroiliitis is found unilaterally, infectious sacroiliitis should be considered as well, especially in the clinical setting of fever, acute pain, and elevated inflammatory blood parameters.[33–35] Furthermore, subperiosteal infiltration and transcapsular edema in adjacent muscles are rather specific for septic arthritis and can thus be used in differentiation with sacroiliitis in SpA. In more advanced stages of infection and osteomyelitis, MRI may show abscess formation, sequestration, and erosions (►**Fig. 8**).[34]

Regarding the imaging of sacral tumors, MRI plays a key role in detection and differential diagnosis, local staging, and posttreatment follow-up.[22] Various tumoral lesions may occur in the sacrum, benign or malignant. While T1-weighted sequences allow precise demarcation of the extent of a tumor, fluid-sensitive and contrast-enhanced MRI sequences can aid the differential diagnosis.[22] Although imaging features sometimes provide specific diagnostic clues for the primary sacral tumors, biopsy often remains necessary to obtain the final diagnosis.[40] The most frequent primary sacral tumor is chordoma, a rare malignant bone tumor

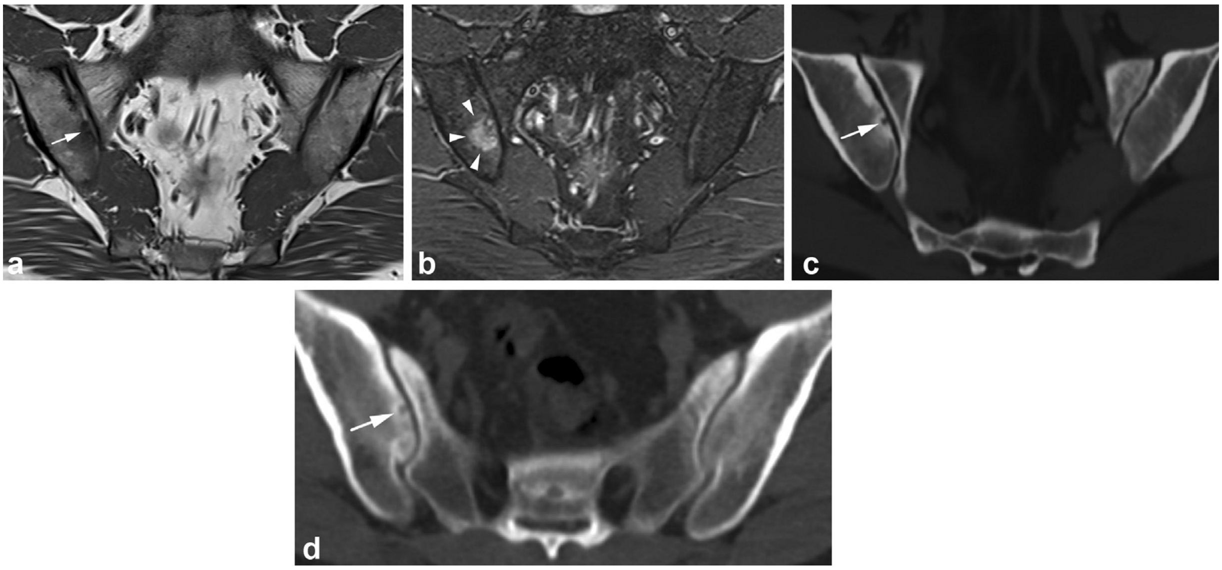

Fig. 7 A 30-year-old man with inflammatory back pain and suspected sacroiliitis. (**a**) Semicoronal T1-weighted image, (**b**) semicoronal short tau inversion recovery image, (**c**) semicoronal synthetic computed tomography (CT) image on magnetic resonance imaging, and (**d**) axial CT image demonstrate an ill-defined erosion with some adjacent sclerosis (arrow), with surrounding bone marrow edema (arrowheads). Note hyperintense signal on T1-weighted images in both joint spaces, clearly delineated from the hypointense sclerotic bone plate.

that arises from notochordal remnants, typically found at the midline in the spine of adults, with predilection in the sacrum and the clivus in the skull base. It is a slow growing, locally aggressive tumor, with extensive bone destruction and soft tissue extension (►**Fig. 9**).[22,41]

Diffusion-Weighted Imaging MRI

Diffusion-weighted imaging (DWI) is based on the Brownian motion of water molecules which can be quantified using the apparent diffusion coefficient (ADC).[42] It separates tissues with differences in free water mobility and therefore allows, for example, differentiation between osteoporotic and pathologic vertebral compression fractures.[43]

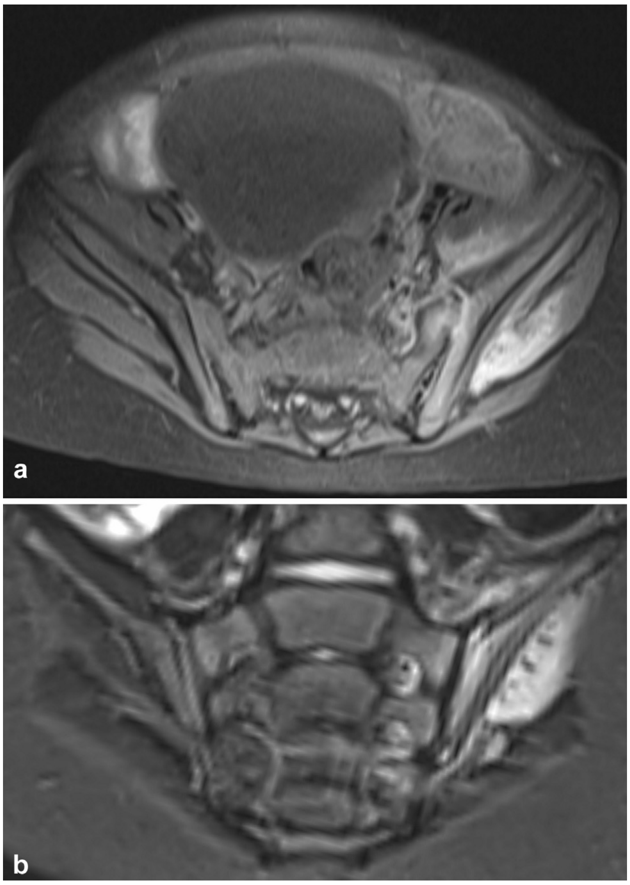

Fig. 8 Magnetic resonance imaging of a 14-month-old boy with fever and limp. (**a**) Axial T1-weigthed spin-echo fat-saturated image after intravenous administration of gadolinium and (**b**) paracoronal T2 turbo inversion recovery magnitude image. There is effusion and synovial enhancement in the left sacroiliac joint, adjacent bone marrow edema, periosteal reaction at the iliac wing, and soft tissue edema.

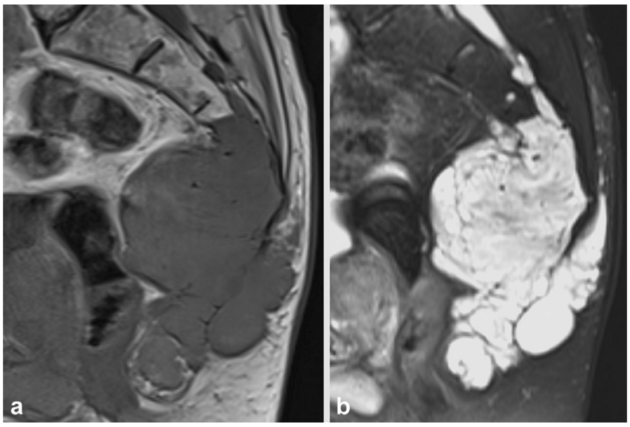

Fig. 9 An 80-year-old-man with sacral chordoma. (**a**) Sagittal T1-weighted magnetic resonance (MR) image shows a sharply demarcated hypointense mass arising from the sacrum, with an extensive soft tissue component. (**b**) Sagittal T2-weighted MR image with fat saturation shows the mass as a multilobular hyperintense mass with hypointense fibrous septations, with extensive bone destruction and soft tissue extension.

DWI may be used for detecting bone marrow lesions because these will stand out with restricted diffusion (and a low ADC value) against normal bone marrow containing more fat.[44] Additionally, DWI can help characterize bone tumors as benign or malignant.[45,46] Furthermore, DWI provided similar diagnostic information as static contrast-enhanced MRI in a study of tumoral soft tissue masses, indicating its usefulness in cases when intravenous contrast cannot be administered.[44,47]

DWI may also be helpful to detect bone marrow edema in active sacroiliitis. Bone marrow edema consists of an increased amount of extracellular water; therefore it demonstrates high signal on DWI. This has been quantified in patients with sacroiliitis using the ADC value, and it appears this adds specificity to the diagnosis, although it does not significantly improve overall diagnostic performance.[48,49] It is therefore not used in daily practice and requires further research.

Susceptibility-Weighted MRI

Susceptibility-weighted imaging (SWI) is a gradient-echo (GE) MRI sequence that uses changes in magnetic susceptibility to enable differentiation of paramagnetic (e.g., calcifications, bone minerals) and diamagnetic (e.g., deoxy hemoglobin, present in blood products) substances.[50] It can be used to detect soft tissue calcifications in (rotator cuff) calcific tendinopathy, to depict osteophytes and syndesmophytes and differentiate them from disk herniations in the spine, and to demonstrate erosions and other bony changes in arthritis.[51] Deppe et al recently found SWI to have higher sensitivity in detection and accuracy in depiction of erosions and sclerosis than T1-weighted imaging in patients with suspected or proven SpA.[52] In addition, SWI demonstrated a higher sensitivity and specificity for the evaluation of vertebral body fractures compared with conventional T1- and T2-weighted sequences, including reliable depiction of fracture lines and cortical breaks.[53] Considering the sacrum as a part of the axial skeleton, these results are promising for the evaluation of sacral and potentially other pelvic fractures on MRI. However, this is still a topic of research and not used in daily practice now.

Three-Dimensional Gradient-Echo Magnetic Resonance Imaging

The 3D GE sequences are high resolution sequences with high spatial resolution, allowing multiplanar reformats that are very helpful in the imaging evaluation of the anatomically complex SIJ. Among others, the 3D volume-interpolated breath-hold examination (VIBE) sequence has been evaluated in different studies and demonstrated higher sensitivity and similar specificity compared with the more classically obtained T1-weighted images for detection of erosions in the SIJ, in patients suspected for SpA.[54,55] In one study with patients diagnosed with SpA, VIBE proved to be more sensitive than CT for erosion detection.[54] This might indicate detection of lesions in the cartilage even before affecting the underlying subchondral bone, allowing early diagnosis. However, caution is warranted because this might also represent an overdiagnosis due to paramagnetic effects.[54] Further research is needed before use of these sequences in routine daily practice can be recommended.

Artificial Intelligence in Sacral Imaging

Over the past few years, development and validation of models of AI in medical imaging, especially deep learning with convolutional neural networks, has resulted in a rapid increasing number of applications. Different types of image-based problem-solving applications have been created, and they can be divided into lesion detection, classification, segmentation, and noninterpretive tasks. As the number of imaging studies increases, these applications can potentially help radiologists in daily practice by automatically performing several rather basic, often repetitive tasks, allowing the radiologist to spend more time on the detailed analysis of complex cases.[56]

Fracture detection on conventional radiographs represents a typical example of a high-volume daily task for the musculoskeletal radiologist. Regarding sacral imaging, a use case was created to detect and classify fractures on pelvic radiographs.[57] The model was able to detect proximal femoral and acetabular fractures with a high (however lower than that of radiologists) diagnostic performance. It demonstrated a lower detection rate for posterior pelvic fractures (including posterior iliac and sacral fractures, and SIJ diastasis), indicating the need for further research and training.[57]

Other models focus on different tasks and pathologies. The algorithm developed by Shenkman et al, for instance, enables automatic detection and grading of sacroiliitis in CT of the abdomen or lower back as an incidental finding, with a sensitivity of 95% for diagnosis and 82% for grading.[58] This can be helpful because structural damage of the SIJ (i.e., erosions, subchondral sclerosis, and, in more advanced stages, ankylosis) may be missed when subtle.

AI models have recently been developed to compute new images, such as synthetic CT images based on specific MRI sequences. In a recent study, MRI-based synthetic CT images outperformed T1-weighted MRI images for detection of erosions, sclerosis, and ankylosis in patients with spondylarthritis, and they were found to be equally reliable as conventional CT.[59] In this way, ionizing radiation can be avoided while obtaining (synthetic) CT images for better evaluation of bony structures, which is a great advantage in an overall young group of patients. Moreover, images representing two completely different techniques are both acquired in one imaging examination (►**Fig. 7**).

Many more AI applications have been developed for use in medical imaging, and numerous more AI models will be created, trained, and validated in the (near) future. However, to our knowledge, none of these deep learning AI tools can perform comprehensive evaluation of any type of imaging study because most models are trained for one single purpose. Therefore, deep learning and other AI tools are likely to support radiologists in their tasks and enhance their capabilities.[56]

Conclusion

As radiologists, we can choose between a variety of different imaging modalities to examine the sacrum. With the advent of new imaging modalities, it is mandatory for us to keep up to date in order to select and use these new techniques properly for the good of our patients.

Conflict of Interest
None declared.

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