Whole-Body Magnetic Resonance Imaging in Rheumatic and Systemic Diseases

From Emerging to Validated Indications

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KEYWORDS

• MR imaging • Whole-body imaging • Diffusion-weighted MR imaging • Rheumatism • Arthritis • Bone • Muscles • Joint

KEY POINTS

- Whole-body (WB) magnetic resonance (MR) imaging plays an essential role in detecting and evaluating the extent of rheumatic disorders affecting the musculoskeletal system, as well as the activity of these diseases and their responses to treatment.
- Numerous multifocal skeletal and neuromuscular disorders benefit from the extended coverage and sensitivity of WB MR imaging to soft tissue alterations for disease diagnosis, quantification, and follow-up.
- The evolution and acceleration of sequences extend the indications of WB MR imaging as a noninvasive, nonirradiating tool in many musculoskeletal disorders, making older irradiating modalities obsolete in many settings.

INTRODUCTION

Whole-body (WB) magnetic resonance (MR) imaging has been the focus of research of many studies during the last 2 decades. This imaging modality offers a large coverage of the skeleton and has a high sensitivity to bone alterations, proving to be effective for the detection of skeletal involvement by oncologic diseases, especially metastases from solid tumors, lymphoma, and multiple myeloma,[1–7] and evaluation of their responses to treatment.[8–10]

Advances in imaging techniques and hardware development have been continuously optimizing the coverage of the examinations and shortening their durations.[11] The sensitivity of MR imaging

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to alterations in tissues such as bone marrow, joints, muscles, ligaments, and tendons, has led to a growing number of applications for this technique outside oncology, from spondyloarthropathies and peripheral seronegative arthritis to other systemic diseases and rheumatic conditions, and, lately, in numerous neuromuscular disorders.[12]

This article highlights the applications of WB MR imaging outside oncology, including rheumatologic disorders, muscle disorders, and bone disorders. Other emerging imaging applications outside these fields are overviewed. In addition, it illustrates the most appropriate MR imaging protocols for each disorder and the upcoming promising role of WB MR imaging in the near future.

RHEUMATOLOGIC DISORDERS

Inflammatory Rheumatisms

Rheumatologic disorders are the most established nononcologic indication of WB MR imaging, especially seronegative rheumatisms, including axial spondyloarthropathies; psoriatic arthritis (PsA); and, less frequently, reactive arthritis, enteropathic arthritis, and undifferentiated spondyloarthritis. WB MR imaging may be said to cover the body from eyes to thighs, which may be sufficient in the evaluation of patients with ankylosing spondyloarthritis (AS) or, more rarely, from head to toes, when the disorder affects distal extremities, as in PsA. Optimized protocols have been developed to cover the upper extremities positioned behind the back or on the abdomen.[13]

Ankylosing spondyloarthritis

AS (**Fig. 1**) typically affects the sacroiliac joints (SIJs) and the discovertebral junctions but may also involve peripheral joints and entheses. Established structural lesions include erosions and new bone formation and can evolve to ankylosis. These lesions are accessible to radiographic examination. MR imaging has extended the sensitivity of imaging tools to prestructural early inflammatory changes taking the form of bone marrow edema (BME) adjacent to joints and discs, enthesitis, and synovitis. In contrast, MR imaging also allows the detection of late chronic and structural changes such as erosions, new bone formation, and ankylosis.

MR imaging of the SIJ and lumbar spine is the modality of choice for early detection of AS and assessment of the response of the disease to treatment.[14–16] MR imaging is sufficient to establish the diagnosis of AS in most patients. Subchondral BME at the level of the SIJ reflects active inflammation and is a major diagnostic criterion for AS.[17] The diagnosis requires the presence of BME on 2 consecutive sections or 2 distinct BME areas in the same section.[18] At the chronic stage or after treatment, BME is replaced by fatty infiltration of the marrow, followed by the development of erosions, sclerosis, and, eventually, ankylosis.[19] At the spinal level, at least 3 typical lesions

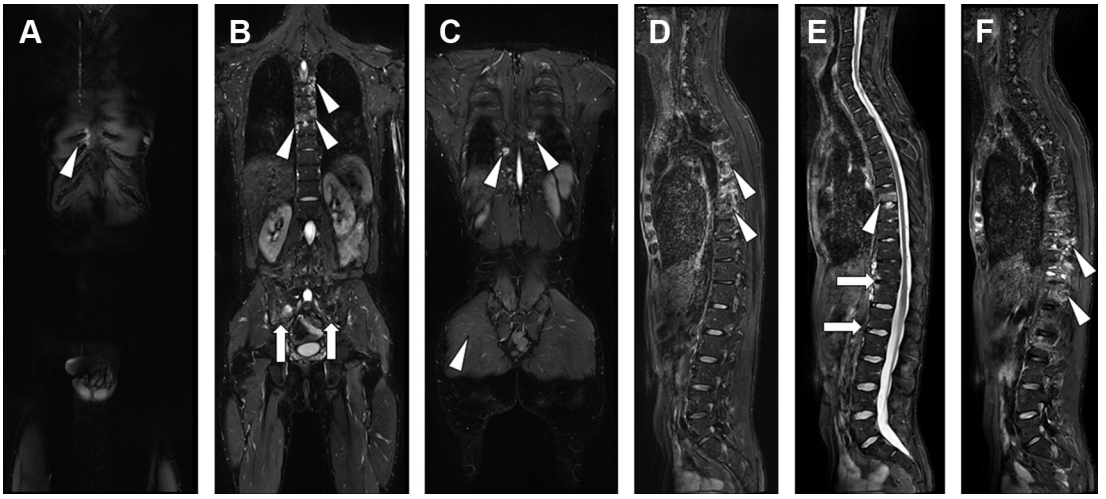

Fig. 1. WB MR imaging from a 33-year-old male patient with AS. Anterior to posterior WB coronal short-tau inversion-recovery (STIR) MR imaging (*A–C*) shows extensive sacroiliac joint (SIJ) inflammation (*arrows* in *B*), along with chondrosternal joint (*arrowhead* in *A*), midthoracic vertebral endplates (*arrowheads* in *B*), and costovertebral (*arrowheads* in *B* and *C*) involvement. Sagittal STIR MR imaging (*D–F*) shows vertebral angle involvement at the thoracolumbar junction (*arrows* in *E*), extensive endplate involvement at the midthoracic level (*arrowhead* in *E*), and severe involvement (*arrowheads* in *D* and *F*) of the lateral portion of the vertebral endplates and costovertebral joints (*arrowheads* in *D* and *F*).

of the anterior or posterior corners are required to establish the diagnosis of inflammatory disease and avoid confusion with degenerative disc disease, which is a frequent condition.[20]

WB MR imaging has the potential advantage of extending the screening of active and chronic lesions of bone margins, joints, tendons, and entheses to the entire axial and peripheral skeleton.[14] It allows the detection of potentially subclinical lesions within the entire spine, pelvis, shoulders, and extremities.[21] Extra-axial lesions are found in half of the patients, consisting most frequently in peripheral synovitis and enthesitis.[16] AS frequently involves the anterior thoracic wall, particularly the manubriosternal and sternoclavicular joint, and the chondrosternal and chondrocostal junctions (see **Fig. 1**).[22] WB MR imaging has driven the attention to specific spine lesions in AS, such as the involvement of costovertebral junctions, the most lateral endplates margins, and the posterior ligaments.[12] Hip involvement by synovitis, bursitis, or enthesitis is also frequent and parallels the disease activity.[23] In addition, the ability of WB MR imaging to detect AS lesions and be used to monitor them in active and chronic/nonactive stages makes it a valuable resource in staging and evaluating the therapeutic response of the disease.[24,25]

The major roles of WB MR imaging in AS are the improvement of diagnostic confidence in patients with negative or ambiguous SIJ observations and the evaluation of the disease activity in the peripheral skeleton in centrally ankylosed disease and the peripheral dominant or exclusive forms of the disease.[12]

Juvenile spondyloarthritis

Juvenile spondyloarthritis (JSA) is a subtype of juvenile idiopathic arthritis associated with the human leukocyte antigen B27 antigen. JSA differs from adult spondyloarthritis by predominantly involving entheses and peripheral joints, mainly of the lower limbs, and its infrequent early involvement of the axial skeleton, which is later affected during the course of the disease.[26,27] WB MR imaging may demonstrate BME and perientheseal soft tissue involvement, synovitis, and joint or bursal fluid. Hips, knees, and ankles are most frequently affected, and tarsitis is a characteristic manifestation of the disease.[28] Synovitis, soft tissue edema, and perientheseal and joint/bursal fluid help distinguish JSA from edemalike findings of the bone marrow that may be seen as a normal variant in healthy children.[28] Arthritis affecting the hips, cervical spine, ankles, or wrists are well-known features of poor prognosis, irrespective of other factors.[29]

Early and accurate disease detection, and especially the detection of factors of poor prognosis in the disease, is essential for appropriate treatment selection. WB MR imaging is now available as a tool for early disease detection in AS and for monitoring activity and guiding therapy initiation and discontinuation.[28]

Psoriatic arthritis

MR imaging is very effective in detecting synovitis and enthesitis in PsA.[30] In addition to the evaluation of the axial skeleton, WB MR imaging can detect and monitor alterations of tenosynovial sheaths and entheses, and may play an important role in therapeutic decisions and evaluation of treatment response.[31]

Rheumatoid arthritis

Rheumatoid arthritis involves mainly the feet and hand joints, but, as a systemic inflammatory disease, it may also affect any joint, tendon, or enthesis in the body. Dedicated MR imaging is highly sensitive in assessing and monitoring disease activity, structural changes, and therapeutic response in rheumatoid arthritis.[32] Recent research has shown that WB MR imaging can be useful in the evaluation of total inflammatory disease load and monitoring of disease activity in axial and peripheral joints and entheses simultaneously.[33]

Systemic Sclerosis

Systemic sclerosis (SSc) or scleroderma is a systemic rheumatic disease characterized by inflammation followed by fibrosis of the skin and subcutaneous tissue, with the potential to also affect other tissues, including muscles, joints, and tendons. Deep vital organs, such as the lungs, heart, esophagus, gut, and kidneys, are frequently involved and affect the prognosis of the disease. Joint and tendon involvement predicts disease progression and muscle involvement and has prognostic value, because it correlates with lesions in vital organs, especially lung fibrosis and myocarditis.[34,35] WB MR imaging can detect a wide variety of musculoskeletal involvement in SSc, including myositis, synovitis, tenosynovitis fasciitis, and enthesitis (**Fig. 2**).[36] This involvement is often generalized and mostly symmetric; it is present in more than 50% of the patients and correlates with the risk of organ damage.[37] WB MR imaging can also be used to monitor treatment response by detecting changes in fascial and subcutaneous thickening and fascial enhancement.[38]

Polymyalgia Rheumatica

Polymyalgia rheumatica (PMR) is a clinically diagnosed rheumatologic disorder associated with a

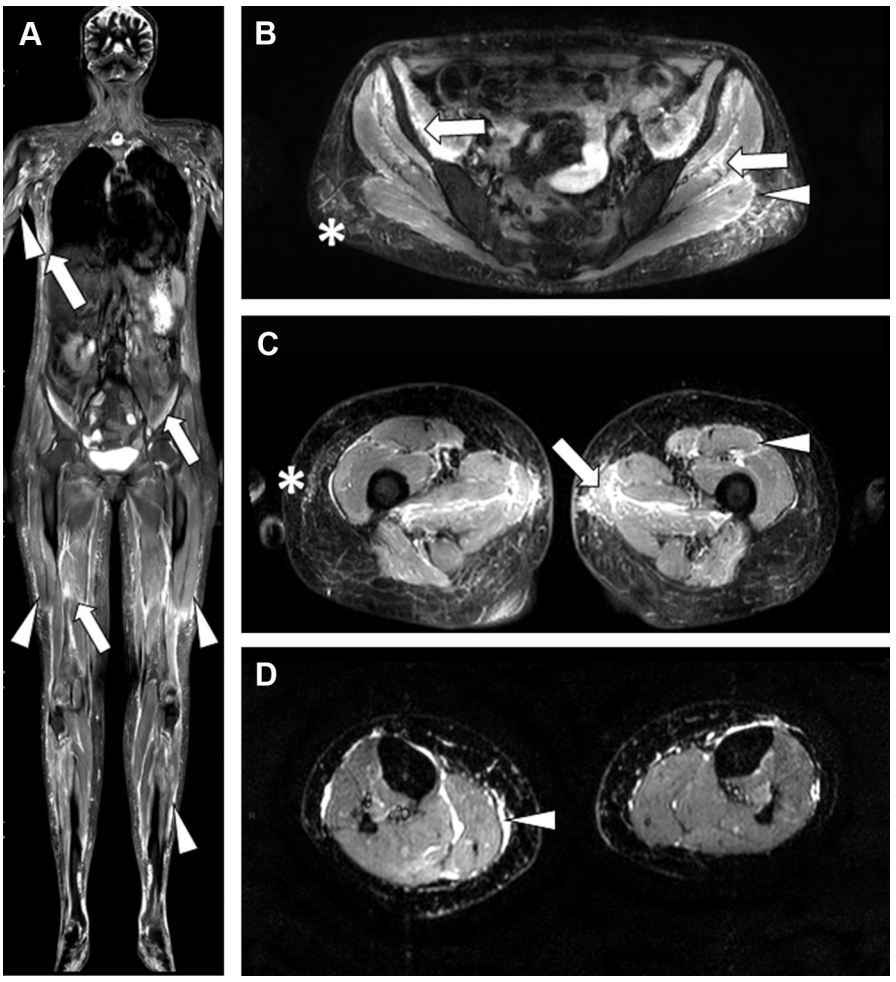

Fig. 2. WB MR imaging from a 53-year-old woman with a severe form of diffuse SSc with myocardial and pericardial involvement, presenting with tendon friction rubs, synovitis, tenosynovitis, and reduced range of motion in shoulders and ankles. Coronal (*A*) and transverse (*B–D*) STIR MR imaging reveals extensive musculoskeletal involvement with concurrent involvement of the muscles (*arrows*), fascias (*arrowheads*), and subcutaneous tissue at the level of the scapular and pelvic girdles (*asterisks*), thoracic and abdominal walls, and lower limbs.

moderate biological inflammatory syndrome and characterized by pain and stiffness affecting the shoulder and pelvic girdles. The symptoms typically show a rapid and impressive response to glucocorticoids. PMR has been regarded as a synovial disease but corresponds more with a periarticular and articular inflammatory process, whereas the presence of extrasynovial features such as bursitis and tendonitis has also been highlighted.[39] Facing uncertain clinical diagnosis, WB MR imaging may also be used to rule out other disorders. However, WB MR imaging might be a valuable tool for a positive diagnosis because extracapsular changes may be regarded as a distinctive feature of PMR, especially when observed around the greater trochanter and ischial tuberosity, in the periacetabular space, and below the symphysis pubis, with no BME.[40] The short-tau inversion recovery (STIR) sequence seems to be the most useful sequence to highlight these abnormalities (**Fig. 3**). The observation of these features identifies a subset of patients who are more responsive to glucocorticoid treatment. The diagnostic value of WB MR imaging in this indication must be compared with that of 18-fluorodeoxyglucose (18-FDG) PET/computed tomography, which shows similar findings (see **Fig. 3**).

SKELETAL MUSCLE DISORDERS

Idiopathic Inflammatory Myopathies

Idiopathic inflammatory myopathies (IIMs) are a heterogeneous group of autoimmune disorders characterized by nonsuppurative muscle inflammation,

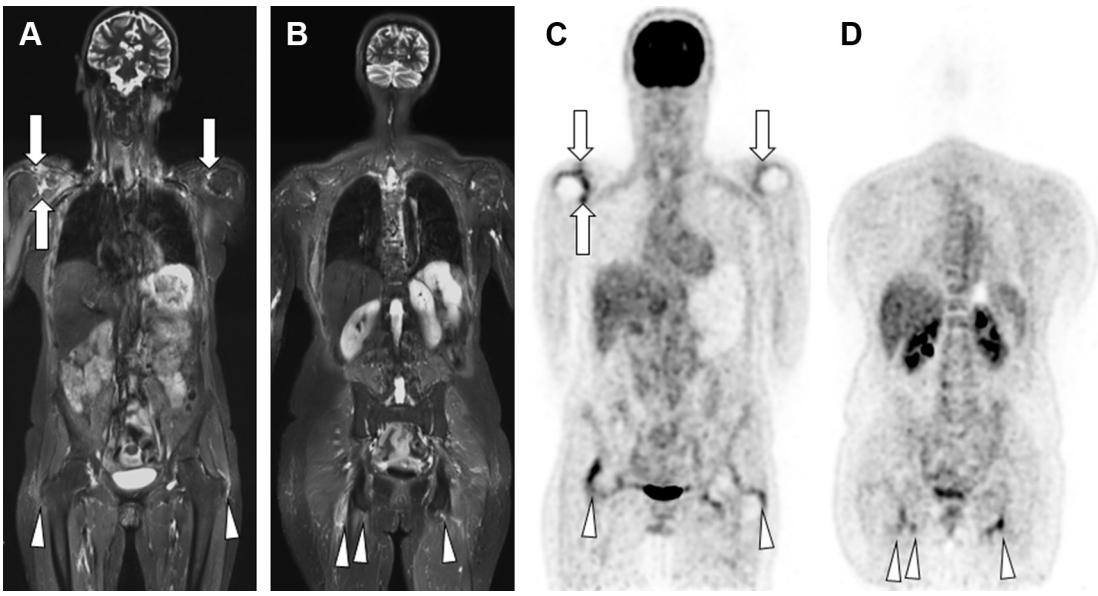

Fig. 3. WB MR imaging from a 52-year-old female patient with polymyalgia rheumatica. Coronal STIR MR imaging (*A, B*) shows bilateral shoulder involvement with inflammatory infiltration of the periarticular soft tissues and synovitis (*arrows* in *A*), hip involvement with peritrochanteric infiltration (*arrowheads* in *A*), and bilateral ischiatic tenosynovitis/bursitis (*arrowheads* in *B*). Corresponding reformatted coronal views of 18-fluorodeoxyglucose PET images (*C, D*) show the same lesions.

which sometimes affects extramuscular tissues. This group includes dermatomyositis (DM), polymyositis (PM), inclusion body myositis (IBM), necrotizing myopathy, and overlap myositis. In necrotizing myopathy, the muscular disorder is associated with a connective tissue disease.

DM, the most frequent type of IIM, affects the muscles and the skin. The onset of DM occurs in childhood, and the disease is more common in girls than in boys.[41] PM affects young adults and does not involve the skin. DM and PM present with muscular weakness, which is more pronounced proximally. IBM affects older male patients and typically involves the distal muscles of the upper limbs and proximal muscles of the lower limbs.[42] DM, PM, and IBM may be paraneoplastic observations associated with malignancy.[43]

MR imaging is very sensitive in detecting active muscle inflammation manifested by a high signal on STIR or water T2 Dixon images.[44] This method is more routinely used as an adjunct diagnostic test, along with clinical manifestations and biological tests such as measurement of muscle enzyme levels. Later in the disease course, MR imaging detects muscle atrophy and fatty involution, which correspond with less active advanced disease. This method also has an important role in guiding muscle biopsy, which is the gold standard for diagnosis of IIM, preventing false-negative results and repeated biopsies. Muscle biopsy should be directed to a site of muscle edema and minimal fatty infiltration.[45] In early forms of the disease in which IIM is suspected despite normal muscle strength and minimal alterations in serum levels of muscle enzyme, MR imaging can be useful in detecting subclinical muscle changes and offers an opportunity for early treatment. In addition, this method allows noninvasive evaluation of treatment response (**Fig. 4**).

An advantage of WB MR imaging is its ability to detect distal and patchy lesions that sometimes are not assessed clinically and may be missed with focused conventional MR imaging.[46] This method also reveals disease activity in muscles that are difficult to examine clinically, detects subcutaneous edema suggestive of DM, and may detect occult malignancy in paraneoplastic forms.[47]

In addition, WB MR imaging may help differentiate between the types of IIM based mainly on the distribution of muscle involvement. DM presents with proximal symmetric involvement of the hip and shoulder girdles, frequently the quadriceps femoris, with edema of subcutaneous tissues and fascia. PM involves the thigh muscles globally or posteriorly, whereas IBM involves the thighs anteriorly.[48] Muscular involvement is patchy in DM and more diffuse in PM and IBM.[49] IBM characteristically affects the distal upper limb and proximal lower limb.[44]

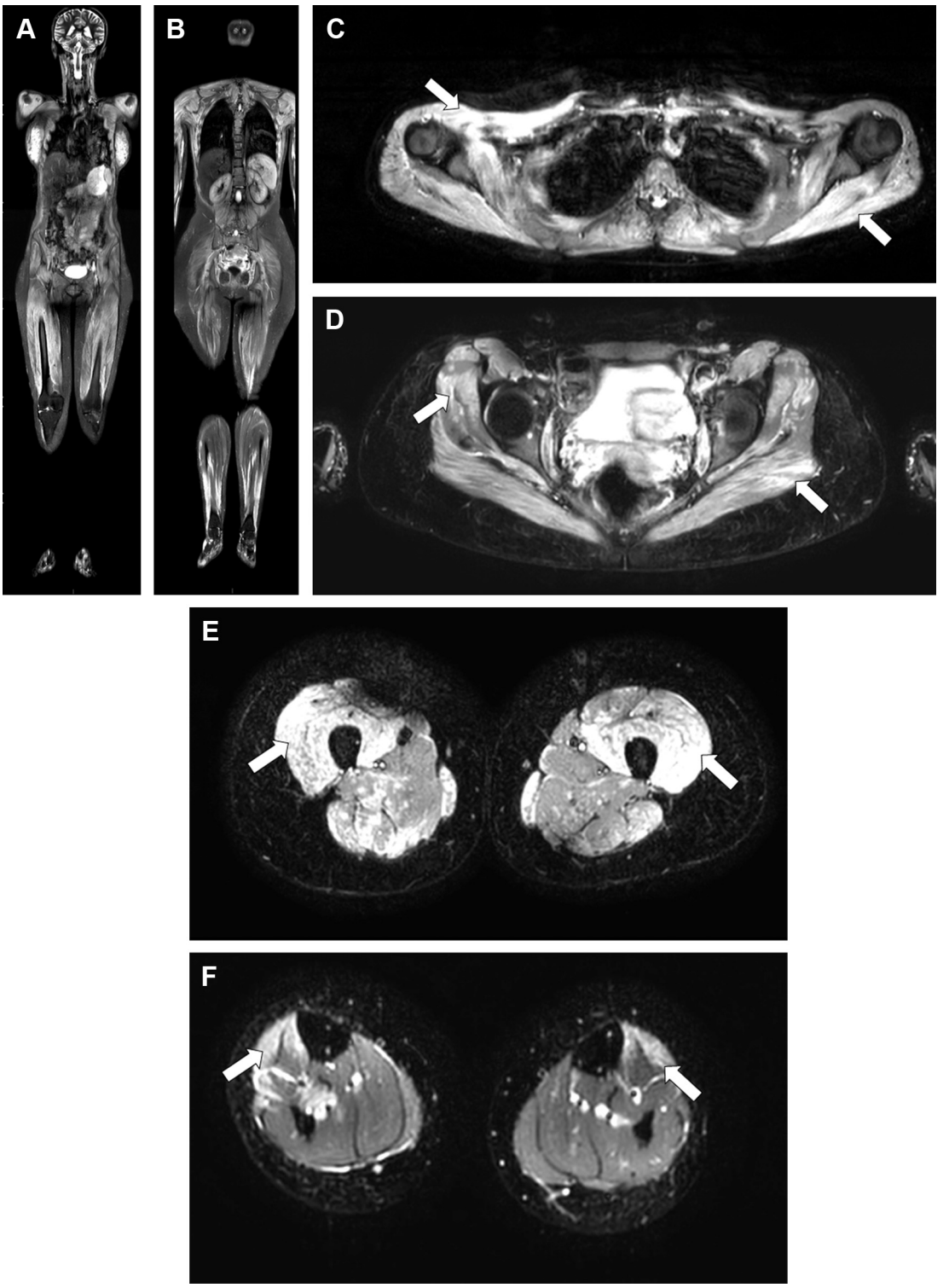

Fig. 4. WB MR imaging from a 26-year-old woman with diffuse muscle pain and increased serum creatine kinase level showing multifocal muscle abnormalities. Coronal (*A*, *B*) and transverse (*C–F*) STIR MR imaging shows severe multifocal (almost diffuse) abnormal signal intensity areas (*arrows*) involving the muscles in the upper and lower limbs. Dermatomyositis with autoantibodies was diagnosed after biopsy of an involved muscle (note the absence of evident subcutaneous tissue abnormalities on WB MR imaging). Corresponding coronal (*G*, *H*) and transverse (*I–L*) MR imaging after a 3-month treatment with high doses of glucocorticoids and methotrexate shows an almost complete disappearance of the muscle abnormalities.

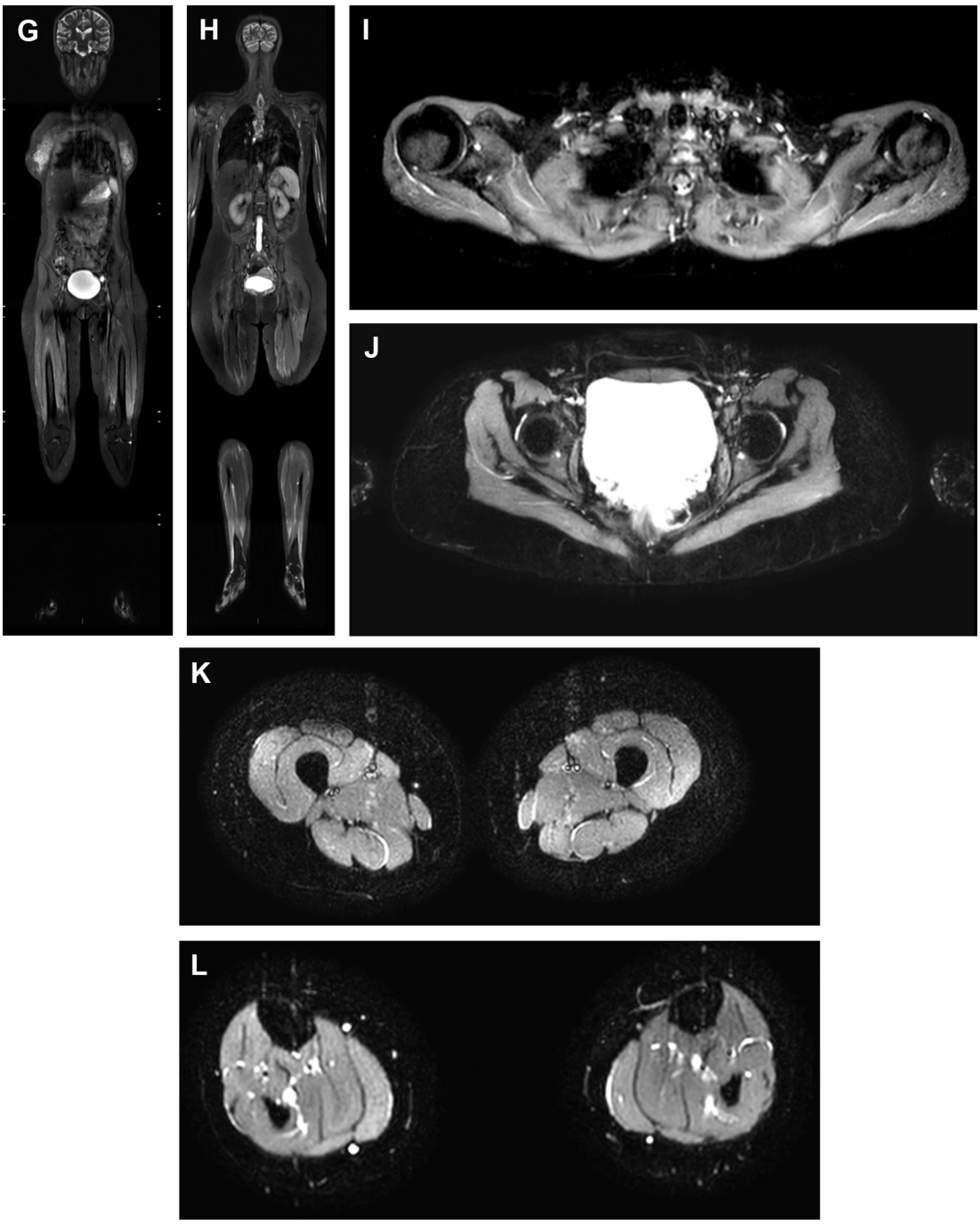

Fig. 4. (*continued*)

In addition to muscle inflammation and end-stage muscle atrophy and fatty transformation in IIM, WB MR imaging is also efficient in detecting steroid-induced myopathies manifested by fatty infiltration and muscle atrophy. In IIM, WB MR imaging detects side effects of steroid use, particularly early osteonecrosis.[50]

Neuromuscular Diseases

WB MR imaging detects asymmetry of affected areas or disease-specific patterns of distribution within the body in neuromuscular disorders such as Duchenne and Becker disease, myotonic dystrophies, facioscapulohumeral muscular dystrophy,

and glycogen storage diseases.[51–53] As in IIM, application of WB MR imaging in these inherited neuromuscular disorders offers valuable information about disease burden, distribution, and involvement of muscles difficult to assess clinically, such as the trunk and paraspinal muscles. WB MR imaging orients biopsy and targeted physiotherapy or functional exercises, depending on the affected muscles. It yields a baseline map of the affected sites, which can be used on follow-up examinations to estimate disease progression and treatment efficacy.

MULTIFOCAL BONE DISORDERS

Synovitis, Acne, Pustulosis, Hyperostosis, and Osteitis Syndrome and Chronic Recurrent Multifocal Osteomyelitis

Synovitis, acne, pustulosis, hyperostosis, and osteitis (SAPHO) and chronic recurrent multifocal osteomyelitis (CRMO) comprise a complex family of inflammatory disorders with a wide range of clinical presentations, of which multifocal aseptic osteitis is the main feature. In SAPHO, aseptic osteitis is associated with a varying range of cutaneous lesions, hyperostosis, and synovitis. CRMO usually consists of aseptic osteomyelitis, often multifocal, observed in a synchronous or metachronous fashion. CRMO is a pediatric condition, whereas SAPHO tends to affect adults between 30 and 50 years of age.[54,55] Many investigators consider CRMO as the pediatric form of SAPHO.[56] The cause of the disease is still unclear and most likely involves a genetic predisposition with an autoinflammatory process,[57] with infection by *Propionibacterium acnes* inconsistently proved in cases of SAPHO.[58]

Patients usually present with nonspecific focal or multifocal symptoms, including pain, swelling, and limited motion, associated with nonspecific serum biomarkers. Although it is possible to have a single affected site, in most cases multiple clinical or subclinical sites are affected at presentation or later in the disease course.

SAPHO and CRMO share as common features a multifocal skeletal involvement, and the observation of relapsing and remitting lesions typically coexisting at different stages. WB MR imaging may highlight several subclinical sites. These disorders also have distinct features, such as the predominant symmetric anterior chest wall involvement in SAPHO, which mainly affects the sternocostal joints, whereas chest wall involvement is less frequent in CRMO and can be limited to an isolated clavicular lesion. In CRMO, the most frequently affected locations are the distal femoral and tibial metaphyses; synovitis is not a characteristic feature, and the involvement of the axial skeleton is less frequent than in SAPHO.[59–63]

The appearance on MR imaging depends on the lesion's age and activity. BME and periosteal reactions are seen in early active stages, whereas fatty involution and sclerosis are characteristic of chronic lesions (Fig. 5). Hyperostosis and paravertebral enthesopathy may be observed in SAPHO.

The diagnoses of CRMO and SAPHO are made by exclusion, because both often mimic other diseases that must be ruled out, such as infectious

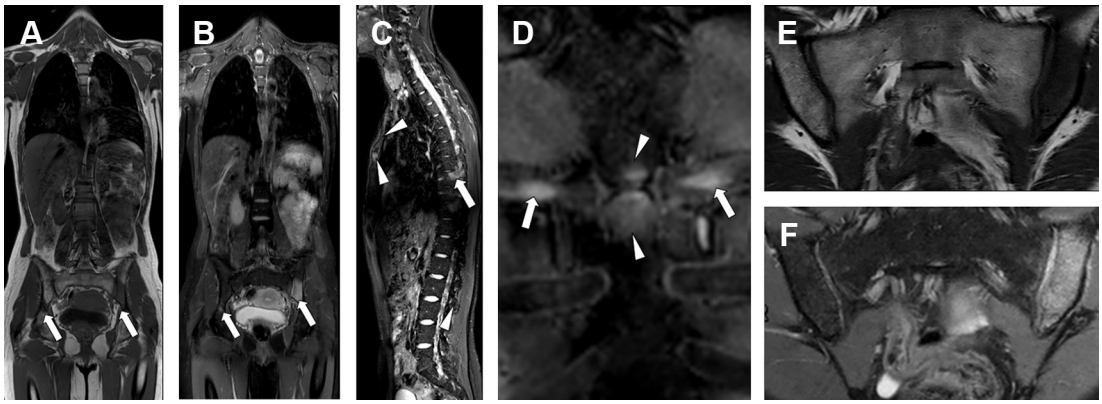

Fig. 5. WB MR imaging from a 38-year-old female patient with SAPHO syndrome (multifocal aseptic osteitis associated with palmoplantar pustulosis). Coronal T1 (*A*) and STIR (*B*) MR imaging of the WB and sagittal STIR images (*C*) of the spine show concurrent bone lesions at the level of the right and left iliac bone, and 1 thoracic vertebra (*arrows* in *A*–*C*) and suggest manubriosternal involvement (*arrowheads* in *C*). Zoomed coronal STIR image of the manubriosternal joint (*D*) confirms the involvement of this joint (*arrowheads* in *D*) and the adjacent second ribs (*arrows* in *D*). Oblique coronal T1 and STIR images (*E*, *F*) of the sacroiliac joints confirm an extensive lesion within the left iliac bone (*arrows* in *E* and *F*). The coexistence of bony lesions and anterior chest wall involvement, along with a clinical history of skin lesions, is pathognomonic of the disease.

osteomyelitis, Ewing sarcoma, Langerhans histiocytosis, osteosarcoma, and leukemia, which explains why, along with the observation of typical skin lesions, WB MR imaging has a major value by showing multifocal involvement by the disease, its characteristic distribution, and the concurrent observation of active and chronic lesions.

Another important role of WB MR imaging is the detection of asymptomatic or subclinical but active disease or lesions, allowing early treatment and preventing late complications such as vertebra plana and kyphosis in children. Standardized evaluation can be used for the assessment of progression, stability, and regression during the disease course and evaluation of therapeutic response.[64]

In addition, WB MR imaging has a major advantage compared with bone scintigraphy (the classic imaging technique in this setting), because it avoids the use of ionizing radiations, especially when considering the pediatric population. In this population, WB MR imaging can easily reveal the typical juxtaphyseal lesions that may be obscured on scintigraphy by normal physiologic uptake of the adjacent physis.[59]

Multifocal Avascular Osteonecrosis

Avascular osteonecrosis (AVN) is a potentially disabling disorder that may lead to devastating secondary arthropathy if early diagnosis and treatment are missed, especially considering that early stages are often asymptomatic.[65] Its multifocal form affects mainly young adults and children treated with a high dose of corticosteroids for rheumatologic or hematologic diseases.

Corticosteroid use is the most common cause of multifocal osteonecrosis; other causes include alcohol abuse, coagulopathies, systemic lupus erythematosus, sickle cell disease, leukemia and lymphoma, renal failure, and Sjögren disease.

MR imaging is the best imaging technique to detect osteonecrosis, showing typical epiphyseal ischemic areas delineated by a geographic rim of low signal on T1-weighted MR imaging.[66] WB MR imaging allows, in a single examination, the evaluation of all possible sites of osteonecrosis in patients at risk and offers a diagnosis of preclinical disease. The risk of collapse may be evaluated in individual lesions to alert both clinician and patient for an early reaction on clinical signs of epiphyseal collapse and to allow early treatment and improvement of the prognosis of the affected joints.[50,67–69]

Hereditary Multiple Exostoses

Hereditary osteochondromatosis or hereditary multiple exostoses is an autosomal dominant condition manifested by multiple benign osteochondromas growing from flat bones or metaphyses of long bones. Most cases are diagnosed in the early teens.[70] Patients may be asymptomatic or show bone deformities and muscular or neurovascular compression.

Malignant transformation is more common in hereditary osteochondromatosis than in sporadic osteochondromas, affecting 3% to 5% of the patients.[70] This complication should be suspected in patients with pain or tumor growth after puberty, cortical destruction, soft tissue mass, and thickened cartilage cap of more than 1.5 to 2 cm, as measured by ultrasonography or MR imaging studies.[71]

MR imaging can show so-called neobursitis or soft tissue edema around the lesion in cases of impingement or fracture of the stalk. Most importantly, this method is able to detect abnormal thickness of the cartilage cap and possible extension within surrounding tissues in cases of malignant transformation. Patients with multiple exostoses require long-term follow-up because of the higher risk of malignant transformation. WB MR imaging may assess multifocal lesions, especially lesions in which clinical examination is limited, such as those in the trunk, and may provide a baseline cartography and quantification of lesions for further systematic or clinically driven follow-up (**Fig. 6**).[72]

Sarcoidosis

Sarcoidosis is a systemic disease that manifests with noncaseating granulomas affecting the bone, liver, spleen, lymph nodes, skin, muscles, and the central nervous system. WB MR imaging is a useful technique to assess these organs (**Fig. 7**). Extrathoracic organ involvement is found in 38% of the patients in WB MR imaging studies, with frequent lesions within the skeleton and muscles, which were probably underestimated before the advent of MR imaging.[73,74] WB MR imaging may show disease extension and activity; the concurrent observation of active and old fatty lesion, especially in the axial skeleton, helps in establishing the differential diagnosis.[75] WB MR imaging is also helpful in the choice of active lesions as biopsy targets.

Langerhans Cell Histiocytosis

Langerhans cell histiocytosis ranges from single-organ involvement to a multisystemic disease affecting children and adolescents and mostly involving the skeleton. The radiographic appearance of the lesions is variable, and the MR imaging findings are nonspecific. Focal bone marrow

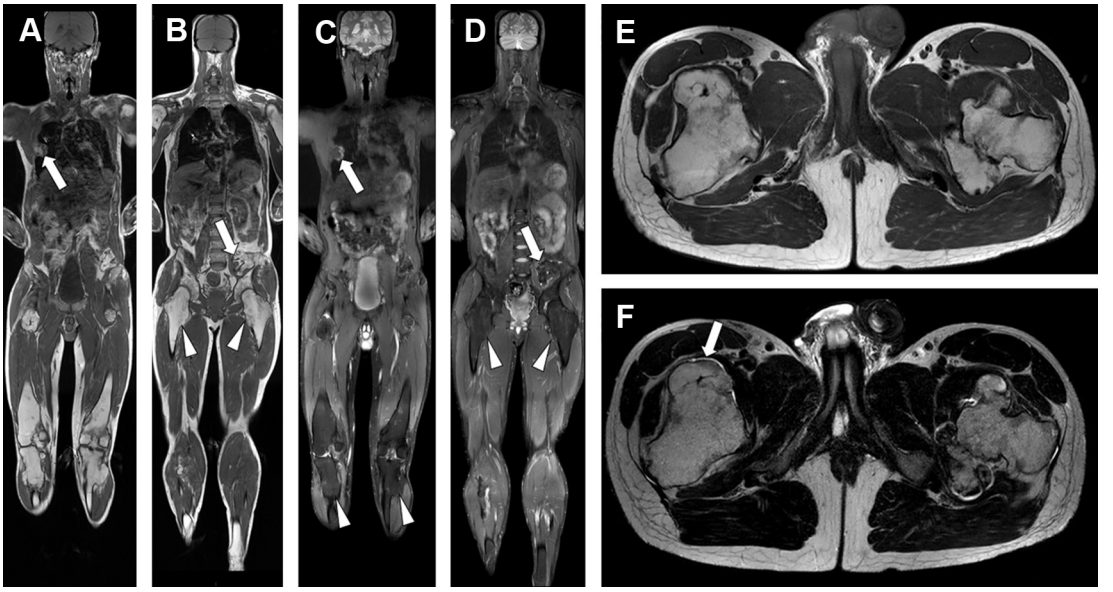

Fig. 6. WB MR imaging from a 22-year-old male patient with hereditary multiple exostoses. Coronal T1 (*A*, *B*) and STIR (*C*, *D*) MR imaging of the WB shows severe deformities predominantly at the level of the hip and knee joints (*arrowheads* in *B* and *D*) and involving the ribs (*arrows* in *A* and *C*) and the left iliac bone (*arrows* in *B* and *D*). Dedicated transverse T1-weighted (*E*) and T2-weighted (*F*) MR imaging shows lesions of the proximal femurs and allows delineation and measurement of the cartilage caps of the exostoses (*arrow* in *F*); these caps remain very thin, ruling out malignant degeneration.

replacement is the usual MR imaging finding, and perilesional edema may be seen in aggressive lesions. Skeletal histiocytosis is a great mimicker and should always be considered in the differential diagnosis of multifocal bone lesions in a child or adolescent. As in osseous sarcoidosis, the concurrent observation of active and quiescent lesions helps in the differential diagnosis with malignancies, although a biopsy may remain necessary. WB MR imaging helps to assess the extent of the disease, including asymptomatic lesions and extraskeletal lesions, and is more sensitive than radiography. Comparisons are ongoing with PET for lesion detection and monitoring.[76–78]

Polyostotic Fibrous Dysplasia

Polyostotic fibrous dysplasia (PFD) is a nonneoplastic skeletal disorder that affects children and is characterized by multifocal proliferation of fibro-osseous tissue in the medullary space. The lesions are usually asymptomatic unless pathologic fractures, deformities, or compression of adjacent structures occur. PFD can be associated with precocious puberty and café-au-lait spots (McCune-Albright syndrome), intramuscular myxomas (Mazabraud syndrome), and endocrinopathies.

The findings of PFD on MR imaging are nonspecific and must be confirmed by radiography once the diagnosis is established. WB MR imaging may be used to evaluate the disease extension and as a baseline assessment for longitudinal monitoring, which may be triggered by the occurrence of symptoms, because the disease may present evolutive phases and complications, mainly pathologic fractures, which may be present insidiously.[79]

OTHER APPLICATIONS AND PERSPECTIVES

Peripheral Nerve Tumors

WB MR imaging has been used to assess tumor extent and to monitor extensive tumors involving peripheral nerves, such as those in neurofibromatosis (**Fig. 8**). Advances in imaging techniques and optimal application of anatomic and diffusion-weighted imaging sequences may offer a valuable approach for morphologic and volumetric analysis of the tumors and an effective tool for detection of malignant transformation.[80,81]

Vascular Malformations

Hemangiomas and lymphangiomas can affect almost every organ, including the skeleton. WB MR imaging is a noninvasive tool for mapping, quantifying, and monitoring these malformations after treatment, regardless of their extension and the involved organs.[82,83] **Fig. 9** shows Parkes Weber syndrome.

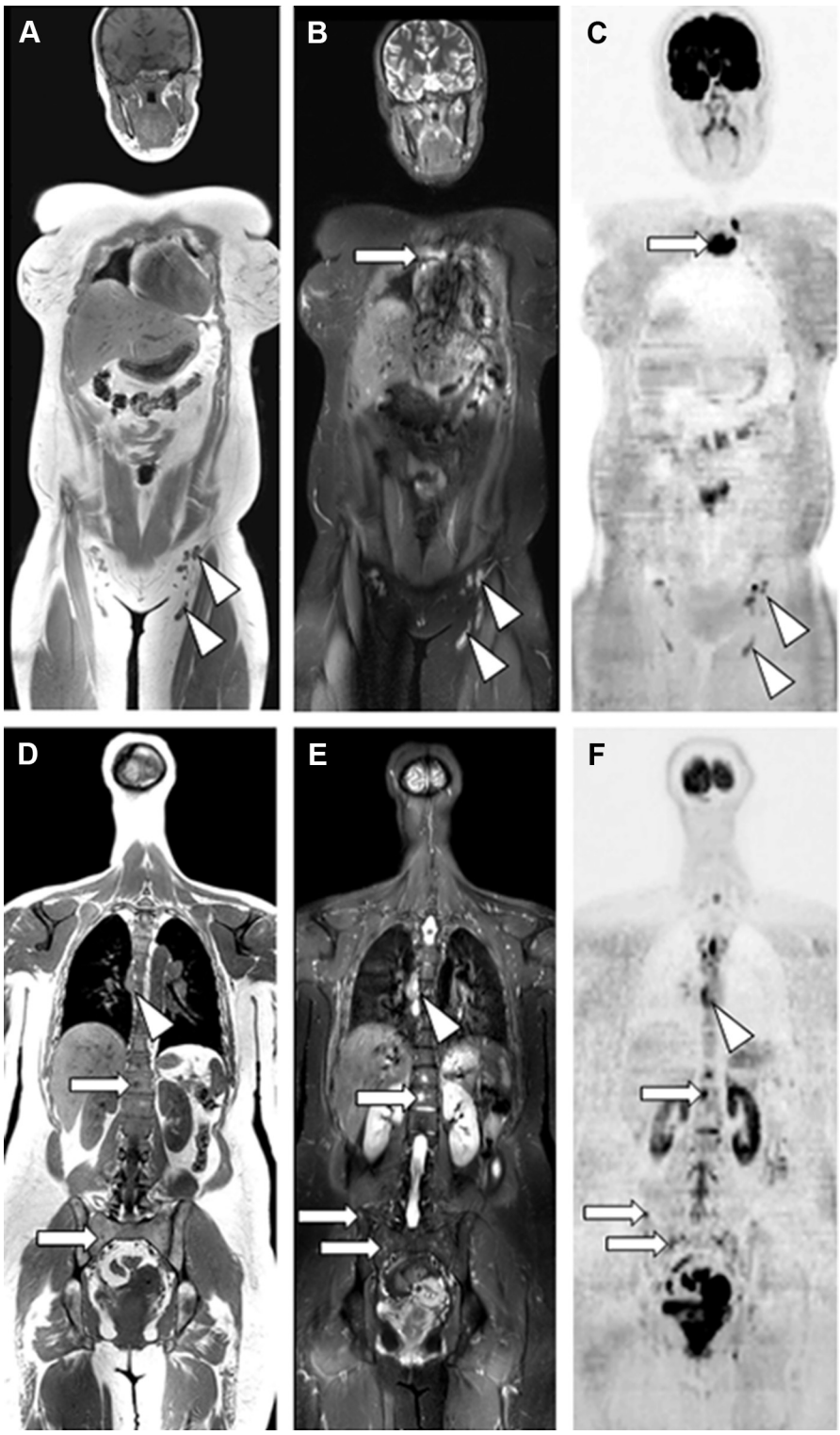

Fig. 7. WB MR imaging from a 34-year-old woman presenting with sarcoidosis. Anterior coronal T1 (*A*), STIR (*B*), and diffusion-weighted (*C*) MR imaging shows bone lesion (*arrows*) in the manubrium sterni, and inguinal lymphadenopathies (*arrowheads*). More posterior coronal slices (*D–F*) show bone lesion (*arrows*) in the spine and pelvis, and mediastinal lymphadenopathies (*arrowheads*). The coexistence of lymphadenopathies involving the mediastinum and inguinal areas is suggestive of sarcoidosis, although other malignant conditions, especially lymphoma, should be ruled out.

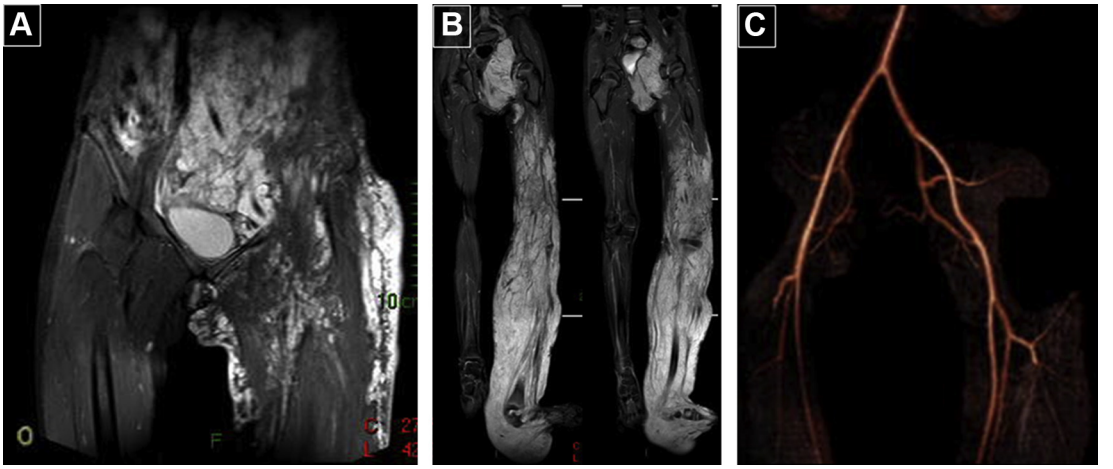

Fig. 8. Plexiform neurofibroma in a 16-year-old patient with neurofibromatosis type I. Coronal STIR-weighted image (*A*) and WB MR imaging (*B*) showing the involvement of the soft tissues, muscle groups, and skin of practically the entire left inferior limb, leading to hypertrophy and deformity. Note on angio-MR imaging (*C*) the tortuosity of the vessels.

Body Fat Mapping

WB MR imaging using a T1 gradient recalled echo (GRE) Dixon sequence has been increasingly used for total body fat quantification and distribution assessment.[84] The main applications of WB MR imaging in this setting are monitoring and treatment of

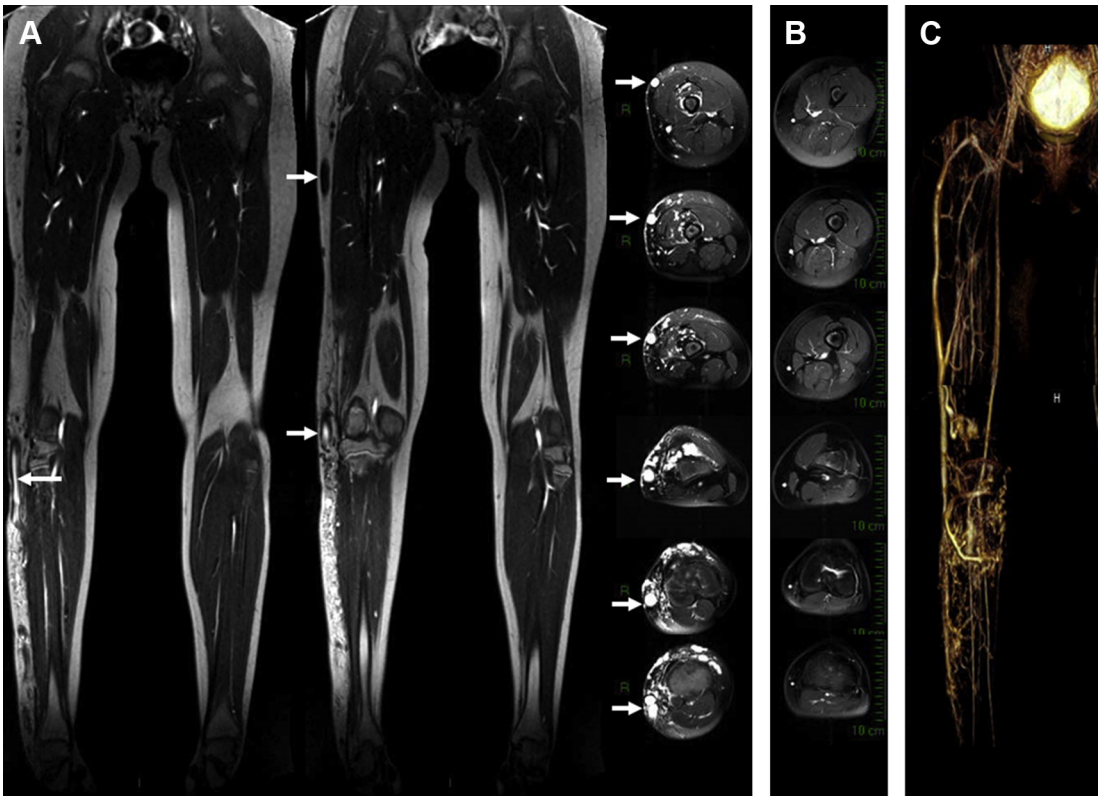

Fig. 9. Parkes Weber syndrome. WB MR imaging coronal T1-weighted images (*A*) and axial STIR images (*B*) showing the enlargement of the right inferior limb caused principally by arteriovenous malformation (*white arrows*). Note on angio-MR imaging (*C*) the arteriovenous malformation without an important fistula component.

patients with obesity and metabolic syndrome, but this method may also be used in training programs of athletes or in syndromes with lipodystrophy, such as neonatal progeroid syndrome, in which generalized loss of subcutaneous fat is a cardinal feature.[85]

Specific Pediatric Applications

In pediatrics, continuous development of the WB MR imaging technique and improvement of this method's sensitivity allow newer applications, including evaluation of fractures/BME and organ injury in nonaccidental trauma,[85] pathologic fractures in susceptible children (such as those with rickets or osteogenesis imperfecta), and hidden focus of inflammation/infection in children with fever of unknown origin.[86] In addition, WB MR imaging has a promising role in virtual autopsy in children and adults.[87]

TECHNICAL NOTE: WHOLE-BODY MAGNETIC RESONANCE IMAGING PROTOCOLS IN NONONCOLOGIC DISORDERS

WB MR imaging protocols are tailored to cover the body and provide exhaustive multiparametric (multisequence) information about the disease, varying with the suspected disorder (**Table 1**).

In axial spondyloarthropathies and rheumatisms, most protocols include coronal T1-weighted and STIR (or fat-saturated T2-weighted) WB images, sagittal T and STIR images of the whole spine, and high-resolution oblique coronal T1-weighted and STIR images of the SIJ. Additional dedicated sequences may be added: high-resolution coronal study of the wrists, hands, and feet in PsA and rheumatoid arthritis; axial images of the hindfoot to detect frequent involvement of the Achilles tendon, ankle tendons, and plantar aponeurosis in seronegative rheumatisms.

Table 1
Summary of current and potential indications of whole-body MR imaging beyond oncology and suggested whole-body MR imaging protocols

	Proposed Protocols		
Disorder	**WB**	**Whole Spine**	**Additional Areas**
Spondyloarthropathies	Coronal (T1 and) STIR DWI (investigational)	Sagittal T1 and STIR	SIJ: oblique coronal T1 and STIR/FST2/T2 Dixon
PsA	Coronal (T1 and) STIR	Sagittal T1 and STIR	Feet/hands: high-resolution STIR/FST2/T2 Dixon
Systemic sclerosis	Coronal STIR	—	Transverse STIR/FST2/Dixon T2 scapular and pelvic girdles *or* on affected areas detected on coronal views
Polymyalgia rheumatica	Coronal STIR *or* FST1 postgadolinium	—	Transverse STIR/FST2/ Dixon T2/
Multifocal nononcologic bone diseases (CRMO, SAPHO, AVN, sarcoidosis, Langerhans cell histiocytosis)	Coronal T1 and STIR	Sagittal T1 and STIR	Transverse T1 or STIR to choose a site for biopsy
Multiple exostoses	Coronal T1 and STIR	—	Adapted plane, high-resolution T2 (T1) of suspect lesions (clinics, coronal study)
Inflammatory myopathies and related disorders	Whole-body (coronal and) transverse T1 and STIR *or* T2 Dixon DWI (investigational)	—	—
Peripheral nerve tumors, vascular malformations	Whole-body (coronal and) transverse T1 and STIR *or* Dixon T2	—	Whole-body T1 after gadolinium injection in some studies
Fat mapping	Whole-body T1 Dixon	—	—

Abbreviations: DWI, diffusion-weighted imaging; FST1, fat-saturated T1; FST2, fat-saturated T2.

This coronal T1-STIR approach is also valuable for most WB MR imaging studies targeting muscles, bones, and nerves, providing a global view of the disease in an acceptable time frame. Transverse sections are also obtained for confident identification of anatomic structures, evaluation of trophicity, and side-by-side comparison of the involvement in muscle disease. These axial slices cover (either systematically or guided by the clinical findings or the findings on global coronal MR imaging views) the scapular and pelvic girdles; lower limbs; and, if the explored field of view allows, the upper limbs as well. These axial slices or tailored planes may also be planned on demand to complement the study of focal bone lesions detected on coronal images, such as exostoses.

The combination of T1 and STIR or fat-saturated T2 images may become obsolete because T2 Dixon images provide in one single sequence combined information on the inflammatory activity through water images and on the fatty degeneration through fat images: this can be transposed to inflammatory and tumoral conditions involving joints, bones, and muscles.[88] Along with anatomic T1, T2, and STIR sequences, the role of diffusion-weighted MR imaging, widely used in WB MR imaging studies performed in oncology and providing functional information on tissues, is also promising in rheumatology, providing sensitivity and high signal to background for subtle lesion screening, as, for example, in spondyloarthropathies.[12]

SUMMARY

WB MR imaging has been proved feasible and useful in numerous nononcologic disorders, of which rheumatologic disorders are the most established, including the study of spondyloarthropathies, PsA, and SSc. WB MR imaging should be used to confirm suspected CRMO and SAPHO syndrome and for an exhaustive evaluation of benign multifocal disorders, such as eosinophilic granuloma and sarcoidosis. It is a noninvasive tool for the diagnosis of inflammatory conditions involving muscles, fascia, and subcutaneous tissue, and its roles range from diagnosis to evaluation of disease burden, choice of lesions for biopsy, and evaluation of treatment response. Tailored protocols have been proposed to address these different indications.

REFERENCES

1. Antoch G, Vogt FM, Freudenberg LS, et al. Whole-body dual-modality PET/CT and whole-body MRI for tumor staging in oncology. JAMA 2003;290(24):3199–206.
2. Baur-Melnyk A, Buhmann S, Becker C, et al. Whole-body MRI versus whole-body MDCT for staging of multiple myeloma. AJR Am J Roentgenol 2008;190(4):1097–104.
3. Eustace S, Tello R, DeCarvalho V, et al. A comparison of whole-body turboSTIR MR imaging and planar 99mTc-methylene diphosphonate scintigraphy in the examination of patients with suspected skeletal metastases. AJR Am J Roentgenol 1997;169(6):1655–61.
4. Horvath LJ, Burtness BA, McCarthy S, et al. Total-body echo-planar MR imaging in the staging of breast cancer: comparison with conventional methods–early experience. Radiology 1999;211(1):119–28.
5. Lauenstein TC, Freudenberg LS, Goehde SC, et al. Whole-body MRI using a rolling table platform for the detection of bone metastases. Eur Radiol 2002;12(8):2091–9.
6. Lauenstein TC, Goehde SC, Herborn CU, et al. Whole-body MR imaging: evaluation of patients for metastases. Radiology 2004;233(1):139–48.
7. Pasoglou V, Michoux N, Peeters F, et al. Whole-body 3D T1-weighted MR imaging in patients with prostate cancer: feasibility and evaluation in screening for metastatic disease. Radiology 2015;275(1):155–66.
8. Lecouvet FE, Larbi A, Pasoglou V, et al. MRI for response assessment in metastatic bone disease. Eur Radiol 2013;23(7):1986–97.
9. Lecouvet FE, Talbot JN, Messiou C, et al. Monitoring the response of bone metastases to treatment with magnetic resonance imaging and nuclear medicine techniques: a review and position statement by the European Organisation for Research and Treatment of Cancer imaging group. Eur J Cancer 2014;50(15):2519–31.
10. Padhani AR, Makris A, Gall P, et al. Therapy monitoring of skeletal metastases with whole-body diffusion MRI. J Magn Reson Imaging 2014;39(5):1049–78.
11. Lecouvet FE. Whole-body MR imaging: musculoskeletal applications. Radiology 2016;279(2):345–65.
12. Lecouvet FE, Michoux N, Nzeusseu Toukap A, et al. The increasing spectrum of indications of whole-body MRI beyond oncology: imaging answers to clinical needs. Semin Musculoskelet Radiol 2015;19(4):348–62.
13. Poggenborg RP, Eshed I, Ostergaard M, et al. Enthesitis in patients with psoriatic arthritis, axial spondyloarthritis and healthy subjects assessed by 'head-to-toe' whole-body MRI and clinical examination. Ann Rheum Dis 2015;74(5):823–9.
14. Althoff CE, Sieper J, Song IH, et al. Active inflammation and structural change in early active axial spondyloarthritis as detected by whole-body MRI. Ann Rheum Dis 2013;72(6):967–73.
15. Barkham N, Keen HI, Coates LC, et al. Clinical and imaging efficacy of infliximab in HLA-B27-positive

patients with magnetic resonance imaging-determined early sacroiliitis. Arthritis Rheum 2009; 60(4):946–54.
16. Rudwaleit M, Schwarzlose S, Hilgert ES, et al. MRI in predicting a major clinical response to anti-tumour necrosis factor treatment in ankylosing spondylitis. Ann Rheum Dis 2008;67(9):1276–81.
17. Rudwaleit M, van der Heijde D, Landewe R, et al. The development of Assessment of SpondyloArthritis international Society classification criteria for axial spondyloarthritis (part II): validation and final selection. Ann Rheum Dis 2009;68(6):777–83.
18. Aydin SZ, Maksymowych WP, Bennett AN, et al. Validation of the ASAS criteria and definition of a positive MRI of the sacroiliac joint in an inception cohort of axial spondyloarthritis followed up for 8 years. Ann Rheum Dis 2012;71(1):56–60.
19. van Onna M, van Tubergen A, van der Heijde DM, et al. Bone marrow edema on magnetic resonance imaging (MRI) of the sacroiliac joints is associated with development of fatty lesions on MRI over a 1-year interval in patients with early inflammatory low back pain: a 2-year followup study. J Rheumatol 2014;41(6):1088–94.
20. Hermann KG, Baraliakos X, van der Heijde DM, et al. Descriptions of spinal MRI lesions and definition of a positive MRI of the spine in axial spondyloarthritis: a consensual approach by the ASAS/OMERACT MRI study group. Ann Rheum Dis 2012;71(8):1278–88.
21. Althoff CE, Appel H, Rudwaleit M, et al. Whole-body MRI as a new screening tool for detecting axial and peripheral manifestations of spondyloarthritis. Ann Rheum Dis 2007;66(7):983–5.
22. Weber U, Lambert RG, Rufibach K, et al. Anterior chest wall inflammation by whole-body magnetic resonance imaging in patients with spondyloarthritis: lack of association between clinical and imaging findings in a cross-sectional study. Arthritis Res Ther 2012;14(1):R3.
23. Jans L, van Langenhove C, Van Praet L, et al. Diagnostic value of pelvic enthesitis on MRI of the sacroiliac joints in spondyloarthritis. Eur Radiol 2014; 24(4):866–71.
24. Appel H, Hermann KG, Althoff CE, et al. Whole-body magnetic resonance imaging evaluation of widespread inflammatory lesions in a patient with ankylosing spondylitis before and after 1 year of treatment with infliximab. J Rheumatol 2007;34(12): 2497–8.
25. Karpitschka M, Godau-Kellner P, Kellner H, et al. Assessment of therapeutic response in ankylosing spondylitis patients undergoing anti-tumour necrosis factor therapy by whole-body magnetic resonance imaging. Eur Radiol 2013;23(7):1773–84.
26. Burgos-Vargas R, Pacheco-Tena C, Vazquez-Mellado J. A short-term follow-up of enthesitis and arthritis in the active phase of juvenile onset spondyloarthropathies. Clin Exp Rheumatol 2002; 20(5):727–31.
27. Tse SM, Laxer RM. New advances in juvenile spondyloarthritis. Nat Rev Rheumatol 2012;8(5):269–79.
28. Aquino MR, Tse SM, Gupta S, et al. Whole-body MRI of juvenile spondyloarthritis: protocols and pictorial review of characteristic patterns. Pediatr Radiol 2015;45(5):754–62.
29. Beukelman T, Patkar NM, Saag KG, et al. 2011 American College of Rheumatology recommendations for the treatment of juvenile idiopathic arthritis: initiation and safety monitoring of therapeutic agents for the treatment of arthritis and systemic features. Arthritis Care Res 2011;63(4):465–82.
30. Coates LC, Hodgson R, Conaghan PG, et al. MRI and ultrasonography for diagnosis and monitoring of psoriatic arthritis. Best Pract Res Clin Rheumatol 2012;26(6):805–22.
31. Weckbach S, Schewe S, Michaely HJ, et al. Whole-body MR imaging in psoriatic arthritis: additional value for therapeutic decision making. Eur J Radiol 2011;77(1):149–55.
32. Ostergaard M, Emery P, Conaghan PG, et al. Significant improvement in synovitis, osteitis, and bone erosion following golimumab and methotrexate combination therapy as compared with methotrexate alone: a magnetic resonance imaging study of 318 methotrexate-naive rheumatoid arthritis patients. Arthritis Rheum 2011;63(12):3712–22.
33. Axelsen MB, Eshed I, Ostergaard M, et al. Monitoring total-body inflammation and damage in joints and entheses: the first follow-up study of whole-body magnetic resonance imaging in rheumatoid arthritis. Scand J Rheumatol 2017;46(4):253–62.
34. Avouac J, Walker UA, Hachulla E, et al. Joint and tendon involvement predict disease progression in systemic sclerosis: a EUSTAR prospective study. Ann Rheum Dis 2016;75(1):103–9.
35. West SG, Killian PJ, Lawless OJ. Association of myositis and myocarditis in progressive systemic sclerosis. Arthritis Rheum 1981;24(5):662–8.
36. Stoenoiu MS, Houssiau FA, Lecouvet FE. Tendon friction rubs in systemic sclerosis: a possible explanation–an ultrasound and magnetic resonance imaging study. Rheumatology 2013;52(3):529–33.
37. Schanz S, Henes J, Ulmer A, et al. Magnetic resonance imaging findings in patients with systemic scleroderma and musculoskeletal symptoms. Eur Radiol 2013;23(1):212–21.
38. Schanz S, Henes J, Ulmer A, et al. Response evaluation of musculoskeletal involvement in patients with deep morphea treated with methotrexate and prednisolone: a combined MRI and clinical approach. AJR Am J Roentgenol 2013;200(4):W376–82.
39. Salvarani C, Cantini F, Olivieri I, et al. Proximal bursitis in active polymyalgia rheumatica. Ann Intern Med 1997;127(1):27–31.

40. Mackie SL, Pease CT, Fukuba E, et al. Whole-body MRI of patients with polymyalgia rheumatica identifies a distinct subset with complete patient-reported response to glucocorticoids. Ann Rheum Dis 2015;74(12):2188–92.
41. Wedderburn LR, Rider LG. Juvenile dermatomyositis: new developments in pathogenesis, assessment and treatment. Best Pract Res Clin Rheumatol 2009; 23(5):665–78.
42. Badrising UA, Maat-Schieman ML, van Houwelingen JC, et al. Inclusion body myositis. Clinical features and clinical course of the disease in 64 patients. J Neurol 2005;252(12):1448–54.
43. Tiniakou E, Mammen AL. Idiopathic inflammatory myopathies and malignancy: a comprehensive review. Clin Rev Allergy Immunol 2017;52(1):20–33.
44. Badrising UA, Kan HE, Verschuuren JJ. MRI in inflammatory myopathies and autoimmune-mediated myositis. In: Weber MA, editor. Magnetic resonance imaging of the skeletal musculature. Berlin: Springer; 2013.
45. Kumar Y, Wadhwa V, Phillips L, et al. MR imaging of skeletal muscle signal alterations: systematic approach to evaluation. Eur J Radiol 2016;85(5): 922–35.
46. Malattia C, Damasio MB, Madeo A, et al. Whole-body MRI in the assessment of disease activity in juvenile dermatomyositis. Ann Rheum Dis 2014;73(6): 1083–90.
47. Day J, Patel S, Limaye V. The role of magnetic resonance imaging techniques in evaluation and management of the idiopathic inflammatory myopathies. Semin Arthritis Rheum 2017;46(5):642–9.
48. Dion E, Cherin P, Payan C, et al. Magnetic resonance imaging criteria for distinguishing between inclusion body myositis and polymyositis. J Rheumatol 2002;29(9):1897–906.
49. Cantwell C, Ryan M, O'Connell M, et al. A comparison of inflammatory myopathies at whole-body turbo STIR MRI. Clin Radiol 2005; 60(2):261–7.
50. Zhen-Guo H, Min-Xing Y, Xiao-Liang C, et al. Value of whole-body magnetic resonance imaging for screening multifocal osteonecrosis in patients with polymyositis/dermatomyositis. Br J Radiol 2017; 90(1073):20160780.
51. Regula JU, Jestaedt L, Jende F, et al. Clinical muscle testing compared with whole-body magnetic resonance imaging in facio-scapulo-humeral muscular dystrophy. Clin Neuroradiol 2016;26(4): 445–55.
52. Shelly MJ, Bolster F, Foran P, et al. Whole-body magnetic resonance imaging in skeletal muscle disease. Semin Musculoskelet Radiol 2010;14(1):47–56.
53. Javan R, Horvath JJ, Case LE, et al. Generating color-coded anatomic muscle maps for correlation of quantitative magnetic resonance imaging analysis with clinical examination in neuromuscular disorders. Muscle Nerve 2013;48(2):293–5.
54. Iyer RS, Thapa MM, Chew FS. Chronic recurrent multifocal osteomyelitis: review. AJR Am J Roentgenol 2011;196(6 Suppl):S87–91.
55. Li C, Zuo Y, Wu N, et al. Synovitis, acne, pustulosis, hyperostosis and osteitis syndrome: a single centre study of a cohort of 164 patients. Rheumatology 2016;55(6):1023–30.
56. Earwaker JW, Cotten A. SAPHO: syndrome or concept? Imaging findings. Skeletal Radiol 2003; 32(6):311–27.
57. Hofmann SR, Roesen-Wolff A, Hahn G, et al. Update: cytokine dysregulation in chronic nonbacterial osteomyelitis (CNO). Int J Rheumatol 2012;2012: 310206.
58. Crouzet J, Claudepierre P, Aribi EH, et al. Two cases of discitis due to *Propionibacterium acnes*. Rev Rhum Engl Ed 1998;65(1):68–71.
59. Falip C, Alison M, Boutry N, et al. Chronic recurrent multifocal osteomyelitis (CRMO): a longitudinal case series review. Pediatr Radiol 2013;43(3):355–75.
60. Greenwood S, Leone A, Cassar-Pullicino VN. SAPHO and recurrent multifocal osteomyelitis. Radiol Clin North Am 2017;55(5):1035–53.
61. Magrey M, Khan MA. New insights into synovitis, acne, pustulosis, hyperostosis, and osteitis (SAPHO) syndrome. Curr Rheumatol Rep 2009;11(5): 329–33.
62. Walsh P, Manners PJ, Vercoe J, et al. Chronic recurrent multifocal osteomyelitis in children: nine years' experience at a statewide tertiary paediatric rheumatology referral centre. Rheumatology 2015; 54(9):1688–91.
63. Colina M, Govoni M, Orzincolo C, et al. Clinical and radiologic evolution of synovitis, acne, pustulosis, hyperostosis, and osteitis syndrome: a single center study of a cohort of 71 subjects. Arthritis Rheum 2009;61(6):813–21.
64. Arnoldi AP, Schlett CL, Douis H, et al. Whole-body MRI in patients with non-bacterial osteitis: radiological findings and correlation with clinical data. Eur Radiol 2017;27(6):2391–9.
65. Kaste SC, Pei D, Cheng C, et al. Utility of early screening magnetic resonance imaging for extensive hip osteonecrosis in pediatric patients treated with glucocorticoids. J Clin Oncol 2015;33(6):610–5.
66. Zibis AH, Varitimidis SE, Dailiana ZH, et al. Fast sequences MR imaging at the investigation of painful skeletal sites in patients with hip osteonecrosis. Springerplus 2015;4:3.
67. Albano D, Patti C, La Grutta L, et al. Osteonecrosis detected by whole body magnetic resonance in patients with Hodgkin lymphoma treated by BEACOPP. Eur Radiol 2017;27(5):2129–36.
68. Castro TC, Lederman H, Terreri MT, et al. The use of joint-specific and whole-body MRI in osteonecrosis:

a study in patients with juvenile systemic lupus erythematosus. Br J Radiol 2011;84(1003):621–8.
69. Miettunen PM, Lafay-Cousin L, Guilcher GM, et al. Widespread osteonecrosis in children with leukemia revealed by whole-body MRI. Clin Orthop Relat Res 2012;470(12):3587–95.
70. Murphey MD, Choi JJ, Kransdorf MJ, et al. Imaging of osteochondroma: variants and complications with radiologic-pathologic correlation. Radiographics 2000;20(5):1407–34.
71. de Souza AMG, Bispo Júnior RZ. Osteochondroma: ignore or investigate? Rev Bras Ortop 2014;49(6):555–64.
72. Herget GW, Kontny U, Saueressig U, et al. Osteochondroma and multiple osteochondromas: recommendations on the diagnostics and follow-up with special consideration to the occurrence of secondary chondrosarcoma. Radiologe 2013;53(12):1125–36 [in German].
73. Hostettler KE, Bratu VA, Fischmann A, et al. Whole-body magnetic resonance imaging in extrathoracic sarcoidosis. Eur Respir J 2014;43(6):1812–5.
74. Wieers G, Lhommel R, Lecouvet F, et al. A tiger man. Lancet 2012;380(9856):1859.
75. Kuzyshyn H, Feinstein D, Kolasinski SL, et al. Osseous sarcoidosis: a case series. Rheumatol Int 2015;35(5):925–33.
76. Goo HW, Yang DH, Ra YS, et al. Whole-body MRI of Langerhans cell histiocytosis: comparison with radiography and bone scintigraphy. Pediatr Radiol 2006;36(10):1019–31.
77. Mueller WP, Melzer HI, Schmid I, et al. The diagnostic value of 18F-FDG PET and MRI in paediatric histiocytosis. Eur J Nucl Med Mol Imaging 2013;40(3):356–63.
78. Dallaudiere B, Kerger J, Malghem J, et al. Adult onset asynchronous multifocal eosinophilic granuloma of bone: an 11-year follow-up. Acta Radiol Open 2015;4(2). 2047981614552217.
79. Ferreira EC, Brito CC, Domingues RC, et al. Whole-body MR imaging for the evaluation of McCune-Albright syndrome. J Magn Reson Imaging 2010;31(3):706–10.
80. Ahlawat S, Fayad LM, Khan MS, et al. Current whole-body MRI applications in the neurofibromatoses: NF1, NF2, and schwannomatosis. Neurology 2016;87(7 Suppl 1):S31–9.
81. Van Meerbeeck SFL, Verstraete KL, Janssens S, et al. Whole body MR imaging in neurofibromatosis type 1. Eur J Radiol 2009;69(2):236–42.
82. Darge K, Jaramillo D, Siegel MJ. Whole-body MRI in children: current status and future applications. Eur J Radiol 2008;68(2):289–98.
83. Kellenberger CJ, Epelman M, Miller SF, et al. Fast STIR whole-body MR imaging in children. Radiographics 2004;24(5):1317–30.
84. Brennan DD, Whelan PF, Robinson K, et al. Rapid automated measurement of body fat distribution from whole-body MRI. AJR Am J Roentgenol 2005;185(2):418–23.
85. O'Neill B, Simha V, Kotha V, et al. Body fat distribution and metabolic variables in patients with neonatal progeroid syndrome. Am J Med Genet A 2007;143A(13):1421–30.
86. Damasio MB, Magnaguagno F, Stagnaro G. Whole-body MRI: non-oncological applications in paediatrics. Radiol Med 2016;121(5):454–61.
87. Griffiths PD, Paley MN, Whitby EH. Post-mortem MRI as an adjunct to fetal or neonatal autopsy. Lancet 2005;365(9466):1271–3.
88. Ozgen A. The value of the T2-weighted multipoint Dixon sequence in MRI of sacroiliac joints for the diagnosis of active and chronic sacroiliitis. AJR Am J Roentgenol 2017;208(3):603–8.