Published in final edited form as:
Semin Arthritis Rheum. 2012 October ; 42(2): 105–118. doi:10.1016/j.semarthrit.2012.03.009.

Magnetic Resonance Imaging of Subchondral Bone Marrow Lesions in Association with Osteoarthritis

Li Xu, MD[*], **Daichi Hayashi, MBBS, PhD**[*], **Frank W. Roemer, MD**[*,†], **David T. Felson, MD, MPH**[‡], and **Ali Guermazi, MD, PhD**[*]

[*]Department of Radiology, Boston University School of Medicine, Boston, MA

[†]Department of Radiology, Klinikum Augsburg, Augsburg, Germany

[‡]Clinical Epidemiology Research and Training Unit, Boston University School of Medicine, Boston, MA

Abstract

Objectives—This nonsystematic literature review provides an overview of magnetic resonance imaging (MRI) of subchondral bone marrow lesions (BMLs) in association with osteoarthritis (OA), with particular attention to the selection of MRI sequences and semiquantitative scoring systems, characteristic morphology, and differential diagnosis. Histologic basis, natural history, and clinical significance are also briefly discussed.

Methods—PubMed was searched for articles published up to 2011, using the keywords bone marrow lesion, osteoarthritis, magnetic resonance imaging, bone marrow edema, histology, pain, and subchondral.

Results—BMLs in association with OA correspond to fibrosis, necrosis, edema, and bleeding of fatty marrow as well as abnormal trabeculae on histopathology. Lesions may fluctuate in size within a short time and are associated with the progression of articular cartilage loss and fluctuation of pain in knee OA. The characteristic subchondral edema-like signal intensity of BMLs should be assessed using T2-weighted, proton density-weighted, intermediate-weighted fat-suppressed fast spin echo or short tau inversion recovery. Several semiquantitative scoring systems are available to characterize and grade the severity of BMLs. Quantitative approaches have also been introduced. Differential diagnoses of degenerative BMLs include a variety of traumatic or nontraumatic pathologies that may appear similar to OA-related BMLs on MRI.

Conclusions—Subchondral BMLs are a common imaging feature of OA with clinical significance and typical signal alteration patterns, which can be assessed and graded by semiquantitative scoring systems using sensitive MRI sequences.

Keywords

bone marrow lesion; bone marrow edema; osteoarthritis; MRI; knee

Address reprint requests to: Daichi Hayashi, MBBS, PhD, Department of Radiology, Boston University School of Medicine, 820 Harrison Avenue, FGH Building, 3rd Floor, Boston, MA 02118. dhayashi@bu.edu.

Ali Guermazi is the president of Boston Imaging Core Lab, LLC (BICL), Boston, MA, a company providing radiological image assessment services. He is a consultant to MerckSerono, Novartis, AstraZeneca, Genzyme and Stryker. Frank Roemer is a shareholder of BICL.

None of the other authors have declared any possible conflict of interest.

Although deterioration of the hyaline articular cartilage and osteophyte formation are considered the hallmarks of knee osteoarthritis (OA), it is now widely accepted that OA is a disease of the whole joint including the subchondral bone, synovium, menisci, and ligaments (1). Subchondral bone marrow edema-like lesions (BMLs) detected on magnetic resonance imaging (MRI) are a frequent finding of OA and have been shown to be associated with clinical manifestations such as pain and with structural progression (2–6). However, the signal alterations of subchondral BMLs are nonspecific, and a variety of traumatic and nontraumatic pathologies may exhibit similar imaging characteristics. Knowledge of the underlying pathophysiology, clinical significance, and natural history of subchondral BMLs is still limited but has been increasing rapidly in recent years. This review article covers the histologic basis, natural history, clinical significance, and MRI evaluation of BMLs in association with OA. We particularly focus on technical aspects of MRI acquisition and semiquantitative scoring systems, the characteristic morphology of BMLs, and on the differential diagnosis of subchondral BMLs.

MATERIALS AND METHODS

A PubMed search for articles published through October 2011 was performed, using the keywords “bone marrow lesion”, “bone marrow edema/oedema”, “bone marrow edema/oedema pattern”. This search strategy yielded 1044 abstracts from all types of publications. The search was then narrowed by adding keywords “osteoarthritis”, “MR imaging”, “histology”, “pain”, and “subchondral”. Relevant to this nonsystematic literature review were original publications that focused on BMLs or BMLs were one of several structural features assessed. Of particular interest were articles on structural/clinical correlations, histopathology, and MRI methodologic studies, as well as articles focusing on the natural history and those assessing interventions. All joints were included. Articles focusing on primary inflammatory arthritides such as rheumatoid arthritis were not considered. The emphasis was on articles published within the last 10 years and written in English, but older publications were also included if considered essential for this review. Altogether, 114 articles (18 articles published between 1957 and 1999 and 96 articles published between 2000 and October 2011) were included. In addition, the reference lists of all articles cited in this review article were screened to complete the literature search. The initial literature search was performed by LX and DH, and screening for relevance was performed by all authors. Evaluation was based on the authors’ own clinical and research experience in the field.

RESULTS

Definition of BMLs

Regional bone marrow signal intensity alteration on MRI was first described by Wilson et al., using the term “bone marrow edema” (BME) to describe MRI findings in painful joints lacking any specific radiographic abnormalities (7). The bone marrow of the affected joint showed ill-defined decreased signal intensity on T1-weighted (T1w) images and increased signal intensity on T2-weighted (T2w) images. A study showed that the areas of these MR signal changes in conjunction with OA corresponded to local scintigraphic uptake (8). The terms BME or BME pattern have been commonly used to describe these ill-defined MR signal changes of bone marrow. However, because studies have shown that various pathologic entities, not just edema, can exhibit BME pattern on MRI, the use of the term “BML” became common, particularly in the OA research community (4,9,10). However, in clinical practice, the terms BME and BME pattern are still more commonly used by radiologists.

According to Roemer et al., traumatic and nontraumatic BMLs should be differentiated, and furthermore, the associated pathology should be carefully described (11). Examples could be "traumatic BML without associated fracture," "traumatic BML in conjunction with osteochondral fracture," "idiopathic nontraumatic BML," "OA-associated BML," "chronic BML in conjunction with osteonecrosis," and so on. For this review, we focused on the discussion of BMLs in association with OA (12). Although most studies of BMLs in conjunction with OA have focused on the knee joint, BMLs are not unique to the knee. The hip is also frequently affected (13–17), as well as the hand (18,19), ankle and foot (20,21), shoulder (22), and spine (23).

Histopathology

Elucidating the histopathology of BMLs in conjunction with OA contributes to better understanding of their natural history and relationship with symptoms. Surprisingly, there is only limited literature that focuses on the correlation between MRI-detected BMLs and histopathology in osteoarthritic joints. All available data are derived from patients who had total knee or hip replacement because of advanced OA (14,15,24,25).

Zanetti et al. reported that the "bone marrow edema pattern zone" mainly consists of normal tissue (53% fatty marrow, 16% intact trabeculae, and 2% blood vessels) and a smaller portion with several types of abnormalities, including bone marrow necrosis (11% of area), necrotic or remodeled trabeculae (8%), bone marrow fibrosis (4%), edema (4%), and bone marrow bleeding (2%) (24). Saadat et al. observed subchondral ingrowth of fibrovascular tissue and increased bone remodeling at the exact anatomical location of the BME pattern on MRI in 3 osteoarthritic knees that were analyzed but did not find edema (25). The authors suspected that increased perfusion to the area owing to the ingrowth of fibrovascular tissue contributed to the BME pattern on MRI.

Similar findings were reported by Taljanovic et al. (14) and Leydet-Quilici et al. (15) in regard to hip OA. Taljanovic et al. described microfractures in different stages of healing that were present in all patients and found that the number of microfractures correlated with the amount of BME visualized by MRI (14). Leydet-Quilici et al. divided bone marrow signal abnormalities into more edema-and necrosis-like patterns and found edema-like patterns to be associated with histologic BME and necrosis-like patterns to be associated with bone marrow fibrosis and necrosis on histology (15).

Natural History of BMLs

The natural history of BMLs includes development, progression, regression, and resolution. Unlike cartilage abnormalities, BMLs represent various histologic findings and can fluctuate in size within a relatively short time (3,26,27).

One longitudinal study assessed subjects with a clinical diagnosis of knee OA and reported that in 0.6% of knees BMLs shrank, in 73% BMLs were stable, and in 27% BMLs increased in size (4). However, the stability of the BMLs may well be because the study used only MRI sequences without fat suppression, rather than MRI sequences that are sensitive to BMLs (ie, fluid sensitive with fat suppression). In contrast, the MOST (Multi-center Osteoarthritis) study, a large-scale longitudinal study of subjects with or at high risk for radiographic knee OA (28), used fat-suppressed MRI to characterize BMLs and found that nearly one-third of knees without baseline BMLs developed new lesions at follow-up, 66% of the prevalent BMLs changed in size, and 50% of subregions with prevalent BMLs showed either regression or resolution (5). In addition, a significant increase in the prevalence of BMLs with an increase in the OA score was observed by Phan et al. (29) and Felson et al. (2).

BMLs and Cartilage Damage

Cross-sectional associations between BMLs and cartilage damage in the same location within the knee joint have been reported (30,31). One study involving 176 healthy, middle-aged women demonstrated a significant cross-sectional positive association between BMLs and cartilage damage after adjusting for the potential risk factors: age, height, weight, and cartilage volume (odds ratio (OR) 1.12 to 2.82) (32). The relationship between longitudinal cartilage loss and BMLs in the same location has also been studied by many investigators. Progression of cartilage damage was found to be an independent risk factor for compartment-specific incident BMLs (33). Also, a number of studies have demonstrated that the severity of BMLs at baseline, progression of BMLs, and newly developing BMLs are independently predictive of compartment-specific longitudinal cartilage loss in patients with or without OA or pain (4–6,32,34,35).

Roemer et al. demonstrated that, when compared to stable BMLs, subregions without BMLs at baseline are associated with a decreased risk of cartilage loss (OR 0.1 to 0.3), while progression of BMLs (OR 1.5 to 5.2) and the development of new BMLs (OR 2.1 to 5.9) are associated with an increased risk of cartilage loss in the same subregion (5). In addition, BML size at baseline was found to be associated with an increased risk of subsequent cartilage loss. A study performed by Hunter et al., including 271 older adults with clinical knee OA, showed that both medial and lateral knee compartments with a higher baseline BML score had greater cartilage loss, and an increase in BMLs was strongly associated with worsening of the cartilage score (4). However, the association of BML change with medial tibiofemoral cartilage loss was not significant after adjusting for alignment. Kothari et al. investigated 177 osteoarthritic knees and found that BMLs at baseline predicted cartilage loss in the same subregion 2 years later, after adjusting for subchondral bone cysts and bone attrition at baseline (OR 1.59 to 8.82) (35).

BMLs and Subchondral Cysts

BMLs are often associated with subchondral cysts, which are characterized by well-defined rounded areas of fluid-like signal intensity on T2w fast spin echo fat-suppressed sequence MR images (24,36). Carrino et al. reported that 92% of incident subchondral cysts developed in regions with BMLs, and the size of BMLs always changed with cyst development (37). In the MOST study it was demonstrated recently that prevalent BMLs showed a strong and significant association with incident cysts in the same subregion (as defined by the Whole Organ Magnetic Resonance imaging Score and WORMS (38)), with an odds ratio of 12.9 after adjustment for full-thickness cartilage loss (36). These investigators all maintained that BMLs can be a precystic lesion (36,37), but that not all BMLs will become cysts (37).

Associations of BMLs with Systemic and Other Structural Features

Systemic factors that have been reported to be related to BMLs in the tibiofemoral joint (TFJ) include age (30,31), male gender (30,31,39), height (30,32), weight (32), and body mass index (31,33,39). For the latter 2, the relation may be present because the knees with BMLs are osteoarthritic. Structural factors other than cartilage and sub-chondral cysts that are commonly investigated in association with BMLs in the knee include malalignment of the TFJ (4), bone area of the lateral tibial plateau (30,32), and meniscal deterioration in the ipsilateral compartment (40–42). Those risk factors were reported to be associated with BMLs in the medial TFJ compartment, lateral TFJ compartment, or total TFJ compartment (Fig. 1). BMLs localized in areas not covered by articular cartilage, such as the interspinous region at the tibia and femoral notch, are known as insertional BMLs and are highly associated with anterior cruciate ligament (ACL) or posterior cruciate ligament damage and may be a consequence of tensile stress on these ligaments (43).

BMLs and Symptoms

Pain in patients with OA may be multifactorial, and one of the major tissues responsible for pain is the subchondral bone. Fibrovascular replacement of adipose marrow tissue within the BMLs was demonstrated by Walsh et al. to be associated with growth factor expression (44). Growth factor may facilitate the growth of sensory nerves or sensitized nerves (45,46), and therefore, it was hypothesized that the growth of fibrovascular tissue within the BMLs may be a source of pain in patients with OA (44). Impaired venous drainage from the BMLs as well as calcitonin gene-related peptide, substance P, and GAP-43/B-50 protein have also been suggested as potential mechanisms of pain generation in patients with OA (47,48).

Felson et al. reported that BMLs are cross-sectionally associated with the presence of pain (OR 3.31, 95% confidence interval 1.54 to 7.41) after adjustment for severity of radiographic OA, effusion, age, and sex, and that large lesions appeared exclusively in the patients with pain (2). Ip et al. reported a significant association between BMLs and pain on climbing stairs but not pain from walking (49). According to Sowers et al., BMLs <1 cm were found more frequently (OR = 5.0; 95% confidence interval = 1.4, 10.5) in the painful knee OA group than the painless knee OA group. However, compared to the group with knee pain but without OA, BMLs were 4 times more likely to occur in the painless knee OA group (50).

Some longitudinal studies have elucidated the relationship between progression of BMLs and pain. Using data from the MOST study, Felson et al. showed that incidence or progression of BMLs was higher at follow-up in subjects with pain than in control subjects without pain (51). Zhang et al. reported that changes in the severity of BMLs were associated with fluctuations in the severity of frequent pain in knees with and without baseline radiographic OA (3).

Although some studies reported no association between pain and BMLs (29,52,53), a recent systematic review including 5 longitudinal and 17 cross-sectional studies demonstrated, with moderate levels of evidence, that BMLs are associated with knee pain (54). Thus, overall evidence suggests that BMLs can be a source of pain in knee OA.

MRI Evaluation of BMLs

Selecting sensitive MRI sequences, using appropriate evaluation methods, and thorough knowledge of the characteristic imaging manifestations of degenerative BMLs on MRI are all indispensable for accurate assessment of BMLs. The general consensus in the OA research and radiological community is that fluid sensitive fat suppressed (FS) sequences, i.e. T2w (long repetition time (TR) and long echo time (TE), e.g. TR/TE =3500/120 ms), proton density-weighted (PDw) (long TR and short TE, e.g. TR/TE = 3500/20) or intermediate-weighted (Iw) (PDw with a TE of about 40 ms, e.g. TR/TE =3500/40) fast spin echo (FSE) sequences, or a short tau inversion recovery (STIR) sequence should be used to assess BMLs (11,52,55–59). Hayashi et al demonstrated, in a direct comparison, that the IW FS sequence depicts more subchondral BMLs and that the FSE sequence depicts the lesions as larger when compared to a gradient echo type sequence (DESS) (60). The aforementioned fluid-sensitive FSE sequences should thus be used for determination of lesion extent whenever the size of a subchondral BML is the focus of attention (Fig. 2). However, one should also note that T2w FS images may exhibit areas of inhomogeneous fat saturation, which can mimic BMLs (57).

Gradient recalled echo (GRE)-type sequences such as spoiled gradient recalled acquisition at steady state (SPGR), fast low angle shot (FLASH), double echo steady state (DESS) and others have been shown to be very sensitive in delineating subchondral cysts (Fig. 2), but these sequences are insensitive to marrow abnormalities due to trabecular magnetic

susceptibility or T2* effects and will not show the true extent of the lesion (57). GRE-type sequences are helpful to distinguish cystic from ill-defined edema-like BMLs (60). On contrast-enhanced MRI, BMLs show avid enhancement and depict the volume of BMLs in an identical fashion to PDw FS or STIR sequences (61,62). For reasons of cost and for patient comfort, optimizing MRI sequence protocols is essential in the routine clinical setting and in epidemiological and clinical studies. While there is no evidence to guide the number of planes in which pulse sequences should be acquired, acquisition of fluid-sensitive fat-suppressed sequences in 2 or 3 orthogonal planes is common to avoid misinterpretation of partial volume effects.

Semiquantitative MRI Assessment of BML—Several semiquantitative scoring systems are available that allow cross-sectional and longitudinal evaluation of BMLs. Analyses based on semiquantitative scoring have added deeply to our understanding of the pathophysiology and natural history of OA, as well as the clinical implications of the structural changes that are assessed (3,4,36,41,51). To date, 4 semiquantitative scoring systems for whole organ assessment of knee OA have been published (Table 1).

The WORMS (38) has been widely used in epidemiologic studies and clinical trials to assess several OA features of the knee (4,63–65). WORMS uses a subregional approach to the scoring of BMLs because recording the exact number of individual lesions is time-consuming and sometimes difficult, as lesions may be directly adjacent to each other or will merge or split in longitudinal assessments (66,67). The Knee Osteoarthritis Scoring System covers MRI-detected OA features much like WORMS (68), except that subchondral BMLs are scored individually for each subregion and each score is differentiated by the size of the lesion. The Boston Leeds Osteoarthritis Knee Score (BLOKS) system uses a subregional division similar to the Knee Osteoarthritis Scoring System.

All 3 of these scoring systems have been published with comparable excellent reliability data (Table 1). Deciding which scoring system should be used for a given study can be tricky. In a recent comparison, MRIs were assessed separately using either the WORMS or the BLOKS systems (66,69). WORMS was found to be superior to BLOKS for assessing BMLs. Two reasons were given for this superior performance: (1) scoring individual lesions over time is not advisable for BMLs, which can split or merge in follow-up scans, making it difficult to characterize change in a single lesion; and (2) BLOKS uses regions that are much larger than WORMS and therefore much less sensitive to changes in lesion volume.

A fourth system, the Magnetic Resonance Imaging Osteoarthritis Knee Score (MOAKS) system (73), was developed in an attempt to rectify these deficiencies in BLOKS and uses an approach to BML scoring that incorporates the WORMS approach of scoring BMLs in a subregional fashion (67). MOAKS scores the number of lesions per subregion, summed lesion size as a percentage of subregional bone volume, and the ratio of noncystic to cystic lesion in the subregion. An important issue to note is that the same lesion may be assigned different grades in different scoring systems (Fig. 2).

Quantitative MRI Assessment of BML—Quantitative measurements of BMLs using MRI provide a tool for evaluating and monitoring lesions that is less observer-dependent than subjective scoring. However, the feathery, ill-defined margin of the lesions makes it difficult to quantify their volume accurately (57). When choosing a sequence for quantification, it is important to consider that the different sequences have several factors that affect the measured T2 relaxation time (70). Static field inhomogeneities and the error propagation introduced by off-resonance effects also affect quantification accuracy (71).

In quantitative MRI, BMLs have to be manually or semiautomatically segmented using a grayscale threshold (20,72). Compared to manual quantification, threshold-based segmentation of BMLs shows higher intra- and interobserver reliability (73,74). Three-dimensional MR spectroscopic imaging may also provide a tool to evaluate BMLs quantitatively in OA, based on the fact that significantly elevated water and unsaturated lipids have been observed in BMLs. The volume of elevated water calculated by 3-dimensional MR spectroscopic imaging correlated significantly with the volume of BMLs based on segmentation on MRI in knees with OA (73).

Manifestations of Degenerative BMLs in Joints Other Than the Knee—The hip is particularly vulnerable to OA as a weight-bearing joint, and OA is the most common disease of the hip joint in adults (75). BMLs associated with OA in the hip appear as an extensive subchondral edema-like pattern within the femoral head and neck and the acetabulum (Fig. 3) (13,76), which corresponds to a combination of edema, fibrosis, and necrosis at histopathology (15). The hip OA MRI scoring system, recently developed by Roemer and colleagues, allows the joint to be evaluated as a whole organ (17). The intra- and interobserver reliabilities of BML scoring with hip OA MRI scoring are 0.72 and 0.85 (weighted kappa), and the intra- and interobserver agreements for all BML scores are 86.7% and 84.9% (17). In the same study, large lesions were found to be significantly related to the Kellgren Lawrence grade of the hip radiograph ($P = 0.002$).

Hand OA is one of the most prevalent forms of OA (77). Tan and colleagues evaluated early hand OA by combining high-resolution MRI with histologic examination and found that the small-joint collateral ligaments and tendons have a central role in the early stages of hand OA (78). The investigators detected BMLs at the collateral ligament origins adjacent to the focal subchondral bone edema. This pattern of BML was found extending to the subchondral regions even where the articular cartilage was well preserved. The pattern was thought to be explained by the “enthesis organ concept” and differed in pathologic content from the subchondral BMLs associated with cartilage degeneration (78,79). A semiquantitative MRI scoring system, the Oslo Hand OA MRI score (18), was recently proposed specifically for hand OA. In this scoring system, subchondral BMLs are scored as the proportion of bone with a lesion in the distal and proximal part of the proximal interphalangeal and distal interphalangeal joints separately; moreover, BMLs at collateral ligament insertion sites are scored separately in the radial and ulnar part of the proximal interphalangeal and distal interphalangeal joints (18). The intra- and interobserver reliabilities were reported as 0.89 and 0.83 for subchondral BML scoring and as 0.81 and 0.42 for BMLs at collateral ligament insertion sites (18).

In OA of the ankle and foot, the metatarsophalangeal joints are commonly affected (80) (Fig. 4A). Unlike the knee and hip, primary OA of the ankle is much less frequent than posttraumatic OA (21). Besides OA, a wide range of inflammatory diseases such as rheumatoid arthritis and seronegative spondyloarthropathies can produce periarticular BMLs in multiple bones. Associated MRI findings such as osteophytes and diffuse articular cartilage loss in OA (Fig. 4B), and periarticular soft-tissue edema, synovitis, and marginal erosions in rheumatoid arthritis, can aid in the diagnosis (81).

Vertebral endplate signal changes are common findings among patients with degenerative disk diseases of the lumbar spine. Modic et al. classified them into 3 types: type 1 changes represent bone marrow edema pattern; type 2 changes are fatty conversion from normal red bone marrow; type 3 changes correspond to subchondral bone sclerosis (82,83). Modic changes are most common at the L4-L5 and L5-S1 levels, usually adjacent to degenerated or herniated intervertebral disks (82–84). Modic type 1 changes are unstable lesions and seem to be strongly associated with low back symptoms and segmental instability (23).

Last, in regard to OA of the shoulder joint (Fig. 5), there is a paucity of publications specifically regarding BMLs in association with glenohumeral OA.

Imaging of BMLs by Other Imaging Modalities

Imaging evaluation of BMLs may also potentially be performed using dual-energy computed tomography (85). This feasibility study showed that the "virtual noncalcium technique" enabled investigators to subtract calcium from cancellous bone, allowing bone marrow assessment in the posttraumatic knee with computed tomography. Whether this technique can be applied to BML assessment in OA is not known at present. Also, nuclear medicine-based imaging techniques reflecting bone metabolism will show increased tracer intake (86,87) or glucose accumulation (88) in areas of BMLs but they are nonspecific and will not add to the differential diagnosis. Conventional radiography, grayscale ultrasound, or Doppler techniques do not allow visualization of BMLs (11). Overall, MRI is the current standard for BML assessment.

Differential Diagnosis

Traumatic BMLs—Trauma-induced BMLs can be differentiated into lesions associated with acute trauma, such as bone contusions, and subacute lesions as a result of chronic overload, such as insufficiency fractures and repetitive microtrauma in conjunction with physical activity. Furthermore, the integrity of the overlying cartilage has to be considered when purely subchondral traumatic BMLs need to be differentiated from concomitant osteochondral and chondral injury.

Bone contusions demonstrate characteristic MRI findings as poorly defined, reticulated, heterogeneous alterations and show a distinct location pattern according to the mechanism of injury (89). Subchondral impaction injuries are a result of severe impaction forces with larger BML volumes and variable degrees of depression of the articular cortical surface, compared to contusions (90,91).

Traumatic BMLs may appear following stress fractures, which include insufficiency fractures and fatigue fractures (92). Insufficiency fractures occur in pathologic bone unable to withstand the stresses of normal activity and can be seen in a variety of diseases such as osteoporosis, osteomalacia, and Paget disease. Subchondral insufficiency fractures mainly involve the femoral head (93–95), although they can involve other joints (96). In contrast, fatigue fractures are the result of excessive strain on normal bone that exceeds the bone's capacity to maintain itself. Athletes, military recruits, and distance runners are particularly prone to fatigue fractures (97–99). The irregular, discontinuous, low-intensity band seen on T1-weighted images surrounded by BML is the characteristic MRI appearance of subchondral stress fractures and corresponds histologically to the fracture line (93,97).

Stress-related BMLs can appear without coexisting degenerative or traumatic changes. Subchondral BMLs related to exercise may appear in a golfer's hand or in the ankles and feet of asymptomatic physically active individuals, with no other associated characteristic MRI findings (100,101). Another form of BML occurs at the insertions of ligaments, especially the ACL and posterior cruciate ligament, and is considered to be due to the traction from ligaments (43). BMLs related to ACL injuries mostly persist after 1 year of follow-up according to 1 report (102).

Nontraumatic BMLs—Nontraumatic BMLs occur in a group of disorders in which an underlying disease or a prior surgical procedure dominates the history, clinical findings, prognosis, and course of the disease. Avascular necrosis (AVN) is depicted as a lesion of high signal intensity surrounded by a reactive rim of low signal intensity on T1-weighted

images, and a mixed high and low signal intensity on T2-weighted images ("the double line sign") is pathognomonic for AVN. This characteristic rim may present postcontrast enhancement on T1w images (103). Progression to larger epiphyseal necrosis and ultimately osteochondral collapse is associated with the appearance of localized BMLs around the infarct. After the femoral head, the knee is the second most frequent site for osteonecrosis: in order of frequency, in the lateral femoral condyle, lateral tibial plateau, and medial femoral condyle (104). Spontaneous osteonecrosis of the knee (SONK) is thought to be caused by an insufficiency fracture, usually in the weight-bearing region of the medial femoral condyle, most often occurring in elderly women (105–107). After the fracture, regions of osteonecrosis develop in the bone superficial to the fracture. The focal subchondral area of low signal intensity adjacent to the subchondral bone plate is a specific MRI finding for SONK, and no postcontrast enhancement of this area is detected on T1w images. A lack of peripheral low signal intensity rim as seen in AVN and nonspecific BML patterns are characteristic of SONK (108).

Bone marrow edema syndrome (BMES) refers to transient clinical conditions with an unknown pathogenic mechanism, such as transient osteoporosis of the hip (which typically affects women during the third trimester of pregnancy, but can also affect middle-aged men and nonpregnant women [109]), regional migratory osteoporosis, complex regional pain syndrome, and reflex sympathetic dystrophy. BMES most commonly affects the proximal femur, sometimes bones around the knee, and infrequently bones in the ankle or foot (110). Reversible large diffuse BMLs without persistent abnormalities suggest a diagnosis of BMES (111). Reactive inflammatory BMLs are most commonly observed in chronic polyarthritis, reactive arthritis, rheumatoid arthritis, and bacterial arthritis. The predominant synovial and periarticular soft tissue involvement and bone erosions are MRI characteristics of the inflammatory arthropathies (112). Disuse osteoporosis is a pathologic condition of bone characterized by focal demineralization that occurs as a result of immobilization. The etiology of this entity appears to be related to loss of mechanical stress with subsequent metabolic changes in the osteoclast and osteoblast activity (113). The fluid-sensitive MR sequences show diffuse multiple dotted hyperintensity throughout the bones involved (114).

Diffuse infiltration of the bone marrow is a common finding of a variety of oncological and hematologic diseases, such as lymphoma, myeloma, and leukemia, as well as some benign tumors, such as Langerhans cell histiocytosis, chondroblastoma, osteoid osteoma, and osteoblastoma. Tumor infiltration presents as well-defined signal alterations with enhancement on postcontrast T1-weighted images, corresponding to the complete replacement of fatty marrow (104). The tumor-associated BML is an ill-defined edema-like signal alteration which surrounds the tumor.

The MRI-detected subchondral BML, comprised of fibrosis, necrosis, edema, and bleeding into fatty marrow in different proportions as well as abnormal trabeculae, is a common finding in patients with OA. Recent studies have shown that BMLs are involved in the progression of articular cartilage loss and fluctuation of pain. Fluid-sensitive T2w fast spin echo fat-suppressed sequence or STIR sequences should be used to assess semiquantitatively the maximum size of BMLs in OA. GRE-type sequences do not allow accurate lesion size estimation but are helpful to distinguish subchondral cysts from BMLs. Several semi-quantitative scoring systems with proven high reader reliability are available to assess and grade the severity of BMLs. A variety of diseases other than OA may show BML-like signal changes that should be distinguished from degenerative BMLs.

Acknowledgments

David T. Felson's work is supported by NIH Grant AR47785.

References

1. Felson DT. An update on the pathogenesis and epidemiology of osteoarthritis. Radiol Clin North Am. 2004; 42:1–9. v. [PubMed: 15049520]
2. Felson DT, Chaisson CE, Hill CL, Totterman SM, Gale ME, Skinner KM, et al. The association of bone marrow lesions with pain in knee osteoarthritis. Ann Intern Med. 2001; 134:541–9. [PubMed: 11281736]
3. Zhang Y, Nevitt M, Niu J, Lewis C, Torner J, Guermazi A, et al. Fluctuation of knee pain and changes in bone marrow lesions, effusions, and synovitis on magnetic resonance imaging. Arthritis Rheum. 2011; 63:691–9. [PubMed: 21360498]
4. Hunter DJ, Zhang Y, Niu J, Goggins J, Amin S, LaValley MP, et al. Increase in bone marrow lesions associated with cartilage loss: A longitudinal magnetic resonance imaging study of knee osteoarthritis. Arthritis Rheum. 2006; 54:1529–35. [PubMed: 16646037]
5. Roemer FW, Guermazi A, Javaid MK, Lynch JA, Niu J, Zhang Y, et al. Change in MRI-detected subchondral bone marrow lesions is associated with cartilage loss: The MOST study. A longitudinal multicentre study of knee osteoarthritis. Ann Rheum Dis. 2009; 68:1461–5. [PubMed: 18829615]
6. Kubota M, Ishijima M, Kurosawa H, Liu L, Ikeda H, Osawa A, et al. A longitudinal study of the relationship between the status of bone marrow abnormalities and progression of knee osteoarthritis. J Orthop Sci. 2010; 15:641–6. [PubMed: 20953925]
7. Wilson AJ, Murphy WA, Hardy DC, Totty WG. Transient osteoporosis: Transient bone marrow edema? Radiology. 1988; 167:757–60. [PubMed: 3363136]
8. McAlindon TE, Watt I, McCrae F, Goddard P, Dieppe PA. Magnetic resonance imaging in osteoarthritis of the knee: Correlation with radiographic and scintigraphic findings. Ann Rheum Dis. 1991; 50:14–9. [PubMed: 1994861]
9. Hunter DJ, Lo GH, Gale D, Grainger AJ, Guermazi A, Conaghan PG. The reliability of a new scoring system for knee osteoarthritis MRI and the validity of bone marrow lesion assessment: BLOKS (Boston Leeds osteoarthritis Knee score). Ann Rheum Dis. 2008; 67:206–11. [PubMed: 17472995]
10. d'Anjou MA, Troncy E, Moreau M, Abram F, Raynauld JP, Martel-Pelletier J, et al. Temporal assessment of bone marrow lesions on magnetic resonance imaging in a canine model of knee osteoarthritis: Impact of sequence selection. Osteoarthritis Cartilage. 2008; 16:1307–11. [PubMed: 18462957]
11. Roemer FW, Frobell R, Hunter DJ, Crema MD, Fischer W, Bohndorf K, et al. MRI-detected subchondral bone marrow signal alterations of the knee joint: Terminology, imaging appearance, relevance and radiological differential diagnosis. Osteoarthritis Cartilage. 2009; 17:1115–31. [PubMed: 19358902]
12. Schett G. Bone marrow edema. Ann N Y Acad Sci. 2009; 1154:35–40. [PubMed: 19250229]
13. Boutry N, Paul C, Leroy X, Fredoux D, Migaud H, Cotten A. Rapidly destructive osteoarthritis of the hip: MR imaging findings. AJR Am J Roentgenol. 2002; 179:657–63. [PubMed: 12185038]
14. Taljanovic MS, Graham AR, Benjamin JB, Gmitro AF, Krupinski EA, Schwartz SA, et al. Bone marrow edema pattern in advanced hip osteoarthritis: Quantitative assessment with magnetic resonance imaging and correlation with clinical examination, radiographic findings, and histopathology. Skeletal Radiol. 2008; 37:423–31. [PubMed: 18274742]
15. Leydet-Quilici H, Le Corroller T, Bouvier C, Giorgi R, Argenson JN, Champsaur P, et al. Advanced hip osteoarthritis: Magnetic resonance imaging aspects and histopathology correlations. Osteoarthritis Cartilage. 2010; 18:1429–35. [PubMed: 20727415]
16. Karachalios T, Karantanas AH, Malizos K. Hip osteoarthritis: What the radiologist wants to know. Eur J Radiol. 2007; 63:36–48. [PubMed: 17555904]
17. Roemer FW, Hunter DJ, Winterstein A, Li L, Kim YJ, Cibere J, et al. Hip osteoarthritis MRI scoring system (HOAMS): Reliability and associations with radiographic and clinical findings. Osteoarthritis Cartilage. 2011; 19:946–62. [PubMed: 21550411]
18. Haugen IK, Lillegraven S, Slatkowsky-Christensen B, Haavardsholm EA, Sesseng S, Kvien TK, et al. Hand osteoarthritis and MRI: Development and first validation step of the proposed Oslo hand osteoarthritis MRI score. Ann Rheum Dis. 2011; 70:1033–8. [PubMed: 21436160]

19. Kalichman L, Hernández-Molina G. Hand osteoarthritis: An epidemiological perspective. Semin Arthritis Rheum. 2010; 39:465–76. [PubMed: 19482338]
20. Schmid MR, Hodler J, Vienne P, Binkert CA, Zanetti M. Bone marrow abnormalities of foot and ankle: STIR versus T1-weighted contrast-enhanced fat-suppressed spin-echo MR imaging. Radiology. 2002; 224:463–9. [PubMed: 12147843]
21. Valderrabano V, Horisberger M, Russell I, Dougall H, Hintermann B. Etiology of ankle osteoarthritis. Clin Orthop Relat Res. 2009; 467:1800–6. [PubMed: 18830791]
22. de Abreu MR, Chung CB, Wesselly M, Jin-Kim H, Resnick D. Acromioclavicular joint osteoarthritis: Comparison of findings derived from MR imaging and conventional radiography. Clin Imaging. 2005; 29:273–7. [PubMed: 15967320]
23. Rahme R, Moussa R. The modic vertebral endplate and marrow changes: Pathologic significance and relation to low back pain and segmental instability of the lumbar spine. AJNR Am J Neuroradiol. 2008; 29:838–42. [PubMed: 18272564]
24. Zanetti M, Bruder E, Romero J, Hodler J. Bone marrow edema pattern in osteoarthritic knees: Correlation between MR imaging and histologic findings. Radiology. 2000; 215:835–40. [PubMed: 10831707]
25. Saadat E, Jobke B, Chu B, Lu Y, Cheng J, Li X, et al. Diagnostic performance of in vivo 3-T MRI for articular cartilage abnormalities in human osteoarthritic knees using histology as standard of reference. Eur Radiol. 2008; 18:2292–302. [PubMed: 18491096]
26. Garnero P, Peterfy C, Zaim S, Schoenharting M. Bone marrow abnormalities on magnetic resonance imaging are associated with type II collagen degradation in knee osteoarthritis: A three-month longitudinal study. Arthritis Rheum. 2005; 52:2822–9. [PubMed: 16145678]
27. Callaghan M, Hutchinson C, Felson D. The relationship between quadriceps arthrogenous inhibition, pain, and bone marrow lesions in subjects with symptomatic patellofemoral osteoarthritis. Osteoarthritis Cartilage. 2011; 18:S197–198.
28. Kellgren JH, Lawrence JS. Radiological assessment of osteo-arthrosis. Ann Rheum Dis. 1957; 16:494–502. [PubMed: 13498604]
29. Phan CM, Link TM, Blumenkrantz G, Dunn TC, Ries MD, Steinbach LS, et al. MR imaging findings in the follow-up of patients with different stages of knee osteoarthritis and the correlation with clinical symptoms. Eur Radiol. 2006; 16:608–18. [PubMed: 16222533]
30. Baranyay FJ, Wang Y, Wluka AE, English DR, Giles GG, Sullivan RO, et al. Association of bone marrow lesions with knee structures and risk factors for bone marrow lesions in the knees of clinically healthy, community-based adults. Semin Arthritis Rheum. 2007; 37:112–8. [PubMed: 17391738]
31. Zhai G, Stankovich J, Cicuttini F, Ding C, Jones G. Familial, structural, and environmental correlates of MRI-defined bone marrow lesions: A sibpair study. Arthritis Res Ther. 2006; 8:R137. [PubMed: 16887014]
32. Guymer E, Baranyay F, Wluka AE, Hanna F, Bell RJ, Davis SR, et al. A study of the prevalence and associations of subchondral bone marrow lesions in the knees of healthy, middle-aged women. Osteoarthritis Cartilage. 2007; 15:1437–42. [PubMed: 17560134]
33. Davies-Tuck ML, Wluka AE, Wang Y, English DR, Giles GG, Cicuttini F. The natural history of bone marrow lesions in community-based adults with no clinical knee osteoarthritis. Ann Rheum Dis. 2009; 68:904–8. [PubMed: 18677011]
34. Dore D, Martens A, Quinn S, Ding C, Winzenberg T, Zhai G, et al. Bone marrow lesions predict site-specific cartilage defect development and volume loss: A prospective study in older adults. Arthritis Res Ther. 2010; 12:R222. [PubMed: 21190554]
35. Kothari A, Guermazi A, Chmiel JS, Dunlop D, Song J, Almagor O, et al. Within-subregion relationship between bone marrow lesions and subsequent cartilage loss in knee osteoarthritis. Arthritis Care Res (Hoboken). 2010; 62:198–203. [PubMed: 20191518]
36. Crema MD, Roemer FW, Zhu Y, Marra MD, Niu J, Zhang Y, et al. Subchondral cystlike lesions develop longitudinally in areas of bone marrow edema-like lesions in patients with or at risk for knee osteoarthritis: Detection with MR imaging—The MOST study. Radiology. 2010; 256:855–62. [PubMed: 20530753]

37. Carrino JA, Blum J, Parellada JA, Schweitzer ME, Morrison WB. MRI of bone marrow edema-like signal in the pathogenesis of subchondral cysts. Osteoarthritis Cartilage. 2006; 14:1081–5. [PubMed: 16806996]
38. Peterfy CG, Guermazi A, Zaim S, Tirman PF, Miaux Y, White D, et al. Whole-organ magnetic resonance imaging score (WORMS) of the knee in osteoarthritis. Osteoarthritis Cartilage. 2004; 12:177–90. [PubMed: 14972335]
39. Dore D, Quinn S, Ding C, Winzenberg T, Zhai G, Cicuttini F, et al. Natural history and clinical significance of MRI-detected bone marrow lesions at the knee: A prospective study in community dwelling older adults. Arthritis Res Ther. 2010; 12:R223. [PubMed: 21190555]
40. Lo GH, Hunter DJ, Nevitt M, Lynch J, McAlindon TE. OAI Investigators Group. Strong association of MRI meniscal derangement and bone marrow lesions in knee osteoarthritis: Data from the osteoarthritis initiative. Osteoarthritis Cartilage. 2009; 17:743–7. [PubMed: 19097919]
41. Englund M, Guermazi A, Roemer FW, Yang M, Zhang Y, Nevitt MC, et al. Meniscal pathology on MRI increases the risk for both incident and enlarging subchondral bone marrow lesions of the knee: The MOST study. Ann Rheum Dis. 2010; 69:1796–802. [PubMed: 20421344]
42. Huétink K, Nelissen RG, Watt I, van Erkel AR, Bloem JL. Localized development of knee osteoarthritis can be predicted from MR imaging findings a decade earlier. Radiology. 2010; 256:536–46. [PubMed: 20587644]
43. Hernández-Molina G, Guermazi A, Niu J, Gale D, Goggins J, Amin S, et al. Central bone marrow lesions in symptomatic knee osteoarthritis and their relationship to anterior cruciate ligament tears and cartilage loss. Arthritis Rheum. 2008; 58:130–6. [PubMed: 18163483]
44. Walsh DA, McWilliams DF, Turley MJ, Dixon MR, Franses RE, Mapp PI, et al. Angiogenesis and nerve growth factor at the osteochondral junction in rheumatoid arthritis and osteoarthritis. Rheumatol Oxf Engl. 2010; 49:1852–61.
45. Nico B, Mangieri D, Benagiano V, Crivellato E, Ribatti D. Nerve growth factor as an angiogenic factor. Microvasc Res. 2008; 75:135–41. [PubMed: 17764704]
46. Ma QP, Woolf CJ. The progressive tactile hyperalgesia induced by peripheral inflammation is nerve growth factor dependent. Neuroreport. 1997; 8:807–10. [PubMed: 9141043]
47. Arnoldi CC, Djurhuus JC, Heerfordt J, Karle A. Intraosseous phlebography, intraosseous pressure measurements and 99mTC-polyphosphate scintigraphy in patients with various painful conditions in the hip and knee. Acta Orthop Scand. 1980; 51:19–28. [PubMed: 7376840]
48. Buma P, Verschuren C, Versleyen D, Van der Kraan P, Oestreicher AB. Calcitonin gene-related peptide, substance P and GAP-43/B-50 immunoreactivity in the normal and arthrotic knee joint of the mouse. Histochemistry. 1992; 98:327–39. [PubMed: 1283163]
49. Ip S, Sayre EC, Guermazi A, Nicolaou S, Wong H, Thorne A, et al. Frequency of bone marrow lesions and association with pain severity: Results from a population-based symptomatic knee cohort. J Rheumatol. 2011; 38:1079–85. [PubMed: 21362771]
50. Sowers MF, Hayes C, Jamadar D, Capul D, Lachance L, Jannausch M, et al. Magnetic resonance-detected subchondral bone marrow and cartilage defect characteristics associated with pain and X-ray-defined knee osteoarthritis. Osteoarthritis Cartilage. 2003; 11:387–93. [PubMed: 12801478]
51. Felson DT, Niu J, Guermazi A, Roemer F, Aliabadi P, Clancy M, et al. Correlation of the development of knee pain with enlarging bone marrow lesions on magnetic resonance imaging. Arthritis Rheum. 2007; 56:2986–92. [PubMed: 17763427]
52. Kornaat PR, Bloem JL, Ceulemans RY, Riyazi N, Rosendaal FR, Nelissen RG, et al. Osteoarthritis of the knee: Association between clinical features and MR imaging findings. Radiology. 2006; 239:811–7. [PubMed: 16714463]
53. Link TM, Steinbach LS, Ghosh S, Ries M, Lu Y, Lane N, et al. Osteoarthritis: MR imaging findings in different stages of disease and correlation with clinical findings. Radiology. 2003; 226:373–81. [PubMed: 12563128]
54. Yusuf E, Kortekaas MC, Watt I, Huizinga TW, Kloppenburg M. Do knee abnormalities visualised on MRI explain knee pain in knee osteoarthritis? A systematic review. Ann Rheum Dis. 2011; 70:60–7. [PubMed: 20829200]

55. Roemer FW, Hunter DJ, Guermazi A. MRI-based semiquantitative assessment of subchondral bone marrow lesions in osteoarthritis research. Osteoarthritis Cartilage. 2009; 17:414–5. Author reply 416–7. [PubMed: 18948039]
56. Crema MD, Roemer FW, Marra MD, Guermazi A. MR imaging of intra- and periarticular soft tissues and subchondral bone in knee osteoarthritis. Radiol Clin North Am. 2009; 47:687–701. [PubMed: 19631076]
57. Peterfy CG, Gold G, Eckstein F, Cicuttini F, Dardzinski B, Stevens R. MRI protocols for whole-organ assessment of the knee in osteoarthritis. Osteoarthritis Cartilage. 2006; 14(Suppl A):A95–111. [PubMed: 16750915]
58. Kornaat PR, Kloppenburg M, Sharma R, Botha-Scheepers SA, Le Graverand MP, Coene LN, et al. Bone marrow edema-like lesions change in volume in the majority of patients with osteoarthritis; associations with clinical features. Eur Radiol. 2007; 17:3073–8. [PubMed: 17823802]
59. Crema MD, Roemer FW, Hayashi D, Guermazi A. Comment on: Bone marrow lesions in people with knee osteoarthritis predict progression of disease and joint replacement: A longitudinal study. Rheumatol Oxf Engl. 2011; 50:996–7. Author reply 997–9.
60. Hayashi D, Guermazi A, Kwoh CK, Hannon MJ, Moore C, Jakicic JM, et al. Semiquantitative assessment of subchondral bone marrow edema-like lesions and subchondral cysts of the knee at 3T MRI: A comparison between intermediate-weighted fat-suppressed spin echo and dual echo Steady State sequences. BMC Musculoskelet Disord. 2011; 12:198. [PubMed: 21906292]
61. Mayerhoefer ME, Breitenseher MJ, Kramer J, Aigner N, Norden C, Hofmann S. STIR vs. T1-weighted fat-suppressed gadolinium-enhanced MRI of bone marrow edema of the knee: Computer-assisted quantitative comparison and influence of injected contrast media volume and acquisition parameters. J Magn Reson Imaging. 2005; 22:788–93. [PubMed: 16270290]
62. Roemer FW, Khrad H, Hayashi D, Jara H, Ozonoff A, Fotinos-Hoyer AK, et al. Volumetric and semiquantitative assessment of MRI-detected subchondral bone marrow lesions in knee osteoarthritis: A comparison of contrast-enhanced and non-enhanced imaging. Osteoarthritis Cartilage. 2010; 18:1062–6. [PubMed: 20472082]
63. Hunter DJ, Zhang YQ, Niu JB, Tu X, Amin S, Clancy M, et al. The association of meniscal pathologic changes with cartilage loss in symptomatic knee osteoarthritis. Arthritis Rheum. 2006; 54:795–801. [PubMed: 16508930]
64. Amin S, Guermazi A, Lavalley MP, Niu J, Clancy M, Hunter DJ, et al. Complete anterior cruciate ligament tear and the risk for cartilage loss and progression of symptoms in men and women with knee osteoarthritis. Osteoarthritis Cartilage. 2008; 16:897–902. [PubMed: 18203629]
65. Reichenbach S, Guermazi A, Niu J, Neogi T, Hunter DJ, Roemer FW, et al. Prevalence of bone attrition on knee radiographs and MRI in a community-based cohort. Osteoarthritis Cartilage. 2008; 16:1005–10. [PubMed: 18367415]
66. Felson DT, Lynch J, Guermazi A, Roemer FW, Niu J, McAlindon T, et al. Comparison of BLOKS and WORMS scoring systems part II. Longitudinal assessment of knee MRIs for osteoarthritis and suggested approach based on their performance: Data from the osteoarthritis initiative. Osteoarthritis Cartilage. 2010; 18:1402–7. [PubMed: 20851202]
67. Roemer FW, Eckstein F, Guermazi A. Magnetic resonance imaging-based semiquantitative and quantitative assessment in osteoarthritis. Rheum Dis Clin North Am. 2009; 35:521–55. [PubMed: 19931802]
68. Kornaat PR, Ceulemans RY, Kroon HM, Riyazi N, Kloppenburg M, Carter WO, et al. MRI assessment of knee osteoarthritis: Knee osteoarthritis scoring system (KOSS)—Inter-observer and intra-observer reproducibility of a compartment-based scoring system. Skeletal Radiol. 2005; 34:95–102. [PubMed: 15480649]
69. Lynch JA, Roemer FW, Nevitt MC, Felson DT, Niu J, Eaton CB, et al. Comparison of BLOKS and WORMS scoring systems part I. Cross sectional comparison of methods to assess cartilage morphology, meniscal damage and bone marrow lesions on knee MRI: Data from the osteoarthritis initiative. Osteoarthritis Cartilage. 2010; 18:1393–401. [PubMed: 20816979]
70. Pai A, Li X, Majumdar S. A comparative study at 3 T of sequence dependence of T2 quantitation in the knee. Magn Reson Imaging. 2008; 26:1215–20. [PubMed: 18502073]

71. Majumdar S, Orphanoudakis SC, Gmitro A, O'Donnell M, Gore JC. Errors in the measurements of T2 using multiple-echo MRI techniques. I. Effects of radiofrequency pulse imperfections. Magn Reson Med. 1986; 3:397–417. [PubMed: 3724419]

72. Roemer FW, Bohndorf K. Long-term osseous sequelae after acute trauma of the knee joint evaluated by MRI. Skeletal Radiol. 2002; 31:615–23. [PubMed: 12395272]

73. Li X, Ma BC, Bolbos RI, Stahl R, Lozano J, Zuo J, et al. Quantitative assessment of bone marrow edema-like lesion and overlying cartilage in knees with osteoarthritis and anterior cruciate ligament tear using MR imaging and spectroscopic imaging at 3 Tesla. J Magn Reson Imaging. 2008; 28:453–61. [PubMed: 18666183]

74. Mayerhoefer ME, Breitenseher M, Hofmann S, Aigner N, Meizer R, Siedentop H, et al. Computer-assisted quantitative analysis of bone marrow edema of the knee: Initial experience with a new method. AJR Am J Roentgenol. 2004; 182:1399–403. [PubMed: 15149981]

75. Hoaglund FT, Shiba R, Newberg AH, Leung KY. Diseases of the hip. A comparative study of Japanese oriental and American white patients. J Bone Joint Surg Am. 1985; 67:1376–83. [PubMed: 4077908]

76. Ragab Y, Emad Y, Abou-Zeid A. Bone marrow edema syndromes of the hip: MRI features in different hip disorders. Clin Rheumatol. 2008; 27:475–82. [PubMed: 17902011]

77. Marshall M, Dziedzic KS, van der Windt DA, Hay EM. A systematic search and narrative review of radiographic definitions of hand osteoarthritis in population-based studies. Osteoarthritis Cartilage. 2008; 16:219–26. [PubMed: 17646114]

78. Tan AL, Toumi H, Benjamin M, Grainger AJ, Tanner SF, Emery P, et al. Combined high-resolution magnetic resonance imaging and histological examination to explore the role of ligaments and tendons in the phenotypic expression of early hand osteoarthritis. Ann Rheum Dis. 2006; 65:1267–72. [PubMed: 16627540]

79. Tan AL, Grainger AJ, Tanner SF, Shelley DM, Pease C, Emery P, et al. High-resolution magnetic resonance imaging for the assessment of hand osteoarthritis. Arthritis Rheum. 2005; 52:2355–65. [PubMed: 16052535]

80. van Saase JL, Vandenbroucke JP, van Romunde LK, Valkenburg HA. Osteoarthritis and obesity in the general population. A relationship calling for an explanation. J Rheumatol. 1988; 15:1152–8. [PubMed: 3172116]

81. Rios AM, Rosenberg ZS, Bencardino JT, Rodrigo SP, Theran SG. Bone marrow edema patterns in the ankle and hindfoot: Distinguishing MRI features. AJR Am J Roentgenol. 2011; 197:W720–729. [PubMed: 21940545]

82. Modic MT, Steinberg PM, Ross JS, Masaryk TJ, Carter JR. Degenerative disk disease: Assessment of changes in vertebral body marrow with MR imaging. Radiology. 1988; 166:193–9. [PubMed: 3336678]

83. Modic MT, Masaryk TJ, Ross JS, Carter JR. Imaging of degenerative disk disease. Radiology. 1988; 168:177–86. [PubMed: 3289089]

84. Karchevsky M, Schweitzer ME, Carrino JA, Zoga A, Montgomery D, Parker L. Reactive endplate marrow changes: A systematic morphologic and epidemiologic evaluation. Skeletal Radiol. 2005; 34:125–9. [PubMed: 15647940]

85. Pache G, Krauss B, Strohm P, Saueressig U, Blanke P, Bulla S, et al. Dual-energy CT virtual noncalcium technique: Detecting posttraumatic bone marrow lesions—Feasibility study. Radiology. 2010; 256:617–24. [PubMed: 20551186]

86. Boegård T, Rudling O, Dahlström J, Dirksen H, Petersson IF, Jonsson K. Bone scintigraphy in chronic knee pain: Comparison with magnetic resonance imaging. Ann Rheum Dis. 1999; 58:20–6. [PubMed: 10343536]

87. Buck FM, Hoffmann A, Hofer B, Pfirrmann CW, Allgayer B. Chronic medial knee pain without history of prior trauma: Correlation of pain at rest and during exercise using bone scintigraphy and MR imaging. Skeletal Radiol. 2009; 38:339–47. [PubMed: 19050867]

88. Nakamura H, Masuko K, Yudoh K, Kato T, Nishioka K, Sugihara T, et al. Positron emission tomography with 18F-FDG in osteoarthritic knee. Osteoarthritis Cartilage. 2007; 15:673–81. [PubMed: 17336549]

89. Sanders TG, Medynski MA, Feller JF, Lawhorn KW. Bone contusion patterns of the knee at MR imaging: Footprint of the mechanism of injury. RadioGraphics. 2000; 20(Spec No):S135–151. [PubMed: 11046168]

90. Frobell RB, Roos HP, Roos EM, Hellio Le Graverand MP, Buck R, Tamez-Pena J, et al. The acutely ACL injured knee assessed by MRI: Are large volume traumatic bone marrow lesions a sign of severe compression injury? Osteoarthritis Cartilage. 2008; 16:829–36. [PubMed: 18206394]

91. Vellet AD, Marks PH, Fowler PJ, Munro TG. Occult posttraumatic osteochondral lesions of the knee: Prevalence, classification, and short-term sequelae evaluated with MR imaging. Radiology. 1991; 178:271–6. [PubMed: 1984319]

92. Resnick, D.; Goergen, T.; Niwayama, G. Physical injury. In: Resnick, D.; Niwayama, G., editors. Diagnosis of bone and joint disorders. Philadelphia (PA): WB Saunders; 1988. p. 2757-3008.

93. Iwasaki K, Yamamoto T, Motomura G, Mawatari T, Nakashima Y, Iwamoto Y. Subchondral insufficiency fracture of the femoral head in young adults. Clin Imaging. 2011; 35:208–13. [PubMed: 21513858]

94. Yamamoto T, Schneider R, Iwamoto Y, Bullough PG. Sub-chondral insufficiency fracture of the femoral head in a patient with systemic lupus erythematosus. Ann Rheum Dis. 2006; 65:837–8. [PubMed: 16699059]

95. Yamanaka H, Goto K, Murata Y, Miyamoto K. Subchondral insufficiency fracture of the femoral head after total knee arthroplasty in a patient with rheumatoid arthritis. Mod Rheumatol. 2006; 16:105–8. [PubMed: 16633931]

96. Tokuya S, Kusumi T, Yamamoto T, Sakurada S, Toh S. Sub-chondral insufficiency fracture of the humeral head and glenoid resulting in rapidly destructive arthrosis: A case report. J Shoulder Elbow Surg. 2004; 13:86–9. [PubMed: 14735080]

97. Song WS, Yoo JJ, Koo KH, Yoon KS, Kim YM, Kim HJ. Sub-chondral fatigue fracture of the femoral head in military recruits. J Bone Joint Surg Am. 2004; 86-A:1917–24. [PubMed: 15342753]

98. Le Gars L, Savy JM, Orcel P, Liote F, Kuntz D, Tubiana JM, et al. Osteonecrosis-like syndrome of the medial tibial plateau can be due to a stress fracture. MR findings in 13 patients. Rev Rhum Engl Ed. 1999; 66:323–30. [PubMed: 10418061]

99. Hoch AZ, Pepper M, Akuthota V. Stress fractures and knee injuries in runners. Phys Med Rehabil Clin N Am. 2005; 16:749–77. [PubMed: 16005402]

100. Grampp S, Henk CB, Mostbeck GH. Overuse edema in the bone marrow of the hand: Demonstration with MRI. J Comput Assist Tomogr. 1998; 22:25–7. [PubMed: 9448756]

101. Lohman M, Kivisaari A, Vehmas T, Kallio P, Malmivaara A, Kivisaari L. MRI abnormalities of foot and ankle in asymptomatic, physically active individuals. Skeletal Radiol. 2001; 30:61–6. [PubMed: 11310200]

102. Frobell RB, Le Graverand MP, Buck R, Roos EM, Roos HP, Tamez-Pena J, et al. The acutely ACL injured knee assessed by MRI: Changes in joint fluid, bone marrow lesions, and cartilage during the first year. Osteoarthritis Cartilage. 2009; 17:161–7. [PubMed: 18760637]

103. Vande Berg BE, Malghem JJ, Labaisse MA, Noel HM, Maldague BE. MR imaging of avascular necrosis and transient marrow edema of the femoral head. RadioGraphics. 1993; 13:501–20. [PubMed: 8316660]

104. Steinbach LS, Suh KJ. Bone marrow edema pattern around the knee on magnetic resonance imaging excluding acute traumatic lesions. Semin Musculoskelet Radiol. 2011; 15:208–20. [PubMed: 21644195]

105. Takeda M, Higuchi H, Kimura M, Kobayashi Y, Terauchi M, Takagishi K. Spontaneous osteonecrosis of the knee: Histopathological differences between early and progressive cases. J Bone Joint Surg Br. 2008; 90:324–9. [PubMed: 18310754]

106. Yamamoto T, Bullough PG. Spontaneous osteonecrosis of the knee: The result of subchondral insufficiency fracture. J Bone Joint Surg Am. 2000; 82:858–66. [PubMed: 10859106]

107. Kattapuram TM, Kattapuram SV. Spontaneous osteonecrosis of the knee. Eur J Radiol. 2008; 67:42–8. [PubMed: 18359599]

108. Lecouvet FE, van de Berg BC, Maldague BE, Lebon CJ, Jamart J, Saleh M, et al. Early irreversible osteonecrosis versus transient lesions of the femoral condyles: Prognostic value of subchondral bone and marrow changes on MR imaging. AJR Am J Roentgenol. 1998; 170:71–7. [PubMed: 9423603]

109. Rocchietti March M, Tovaglia V, Meo A, Pisani D, Tovaglia P, Aliberti G. Transient osteoporosis of the hip. Hip Int. 2010; 20:297–300. [PubMed: 20640992]

110. Sprinchorn AE, O'Sullivan R, Beischer AD. Transient bone marrow edema of the foot and ankle and its association with reduced systemic bone mineral density. Foot Ankle Int. 2011; 32:S508–512. [PubMed: 21733459]

111. Korompilias AV, Karantanas AH, Lykissas MG, Beris AE. Bone marrow edema syndrome. Skeletal Radiol. 2009; 38:425–36. [PubMed: 18629460]

112. Haavardsholm EA, Bøyesen P, Østergaard M, Schildvold A, Kvien TK. Magnetic resonance imaging findings in 84 patients with early rheumatoid arthritis: Bone marrow oedema predicts erosive progression. Ann Rheum Dis. 2008; 67:794–800. [PubMed: 17981915]

113. Takata S, Yasui N. Disuse osteoporosis. J Med Invest. 2001; 48:147–56. [PubMed: 11694954]

114. de Abreu MR, Wesselly M, Chung CB, Resnick D. Bone marrow MR imaging findings in disuse osteoporosis. Skeletal Radiol. 2011; 40:571–5. [PubMed: 20953606]

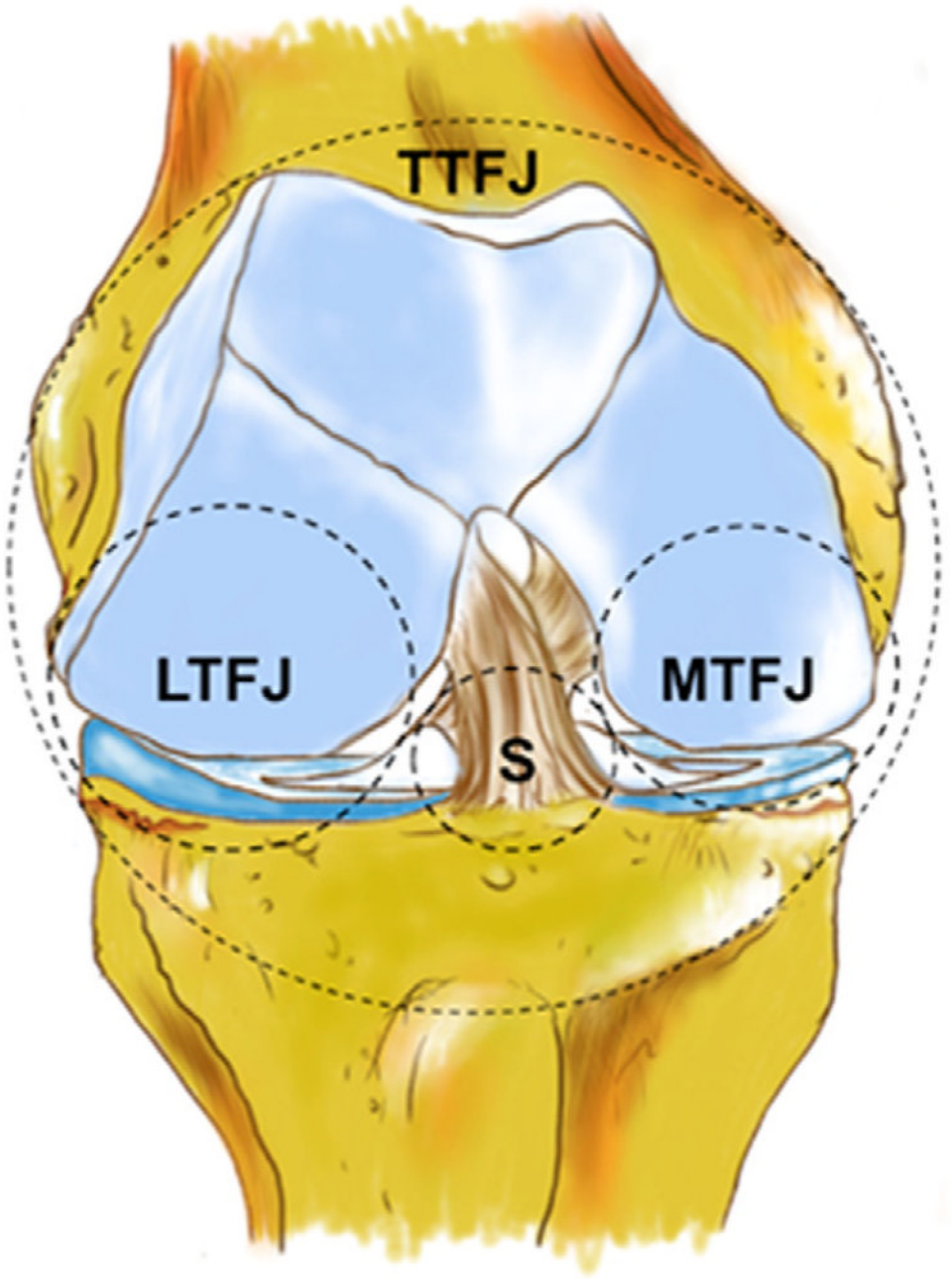

Figure 1.
Different compartments of the tibiofemoral joint of the knee. (Color version of figure is available online.)

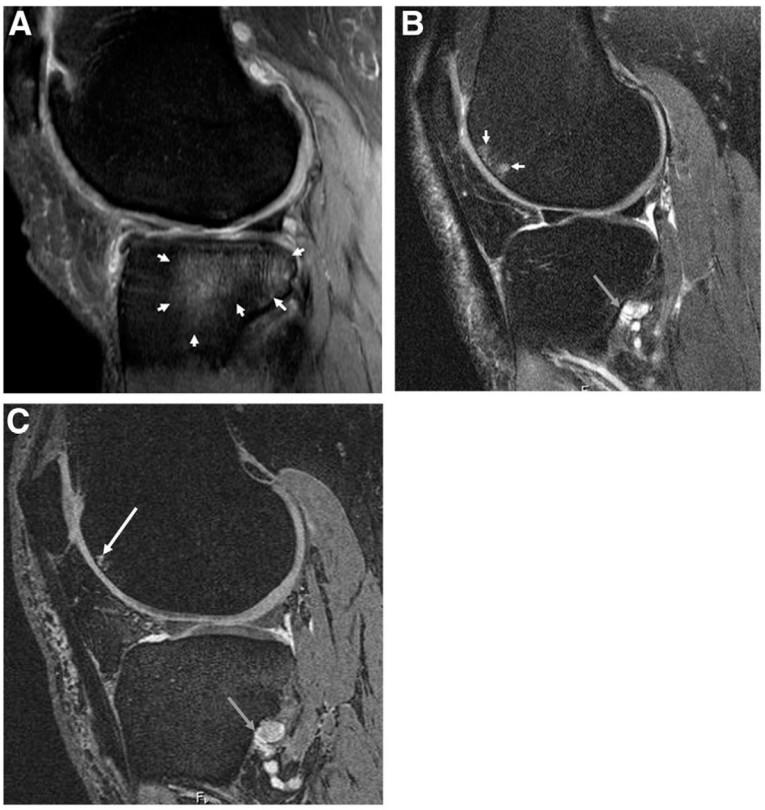

Figure 2.

BMLs in knee osteoarthritis in a 65-year-old woman. (A) Sagittal fat-suppressed proton density-weighted MRI (TR/TE = 3500/20) shows a large BML (short white arrows) involving the central and posterior subregions of the lateral tibia. In the Magnetic Resonance Imaging Osteoarthritis Knee Score (MOAKS), the BML is scored grade 3 (3 = >66% of the region) for size in both the central and the posterior subregions. This lesion would also be scored as a 3 using the Whole Organ Magnetic Resonance Imaging Score (WORMS). (B) Sagittal fat-suppressed intermediate-weighted MRI (TR/TE = 3200/30) shows a subchondral BML in the lateral trochlea (short white arrows), which is scored as grade 2 by MOAKS and grade 3 by WORMS. Also note that the presence of a septated proximal tibiofibular joint cyst (long gray arrow), which represents a synovial cystic change related to the degenerative disease, and superficial diffuse thinning of trochlear cartilage (no arrow). (C) Sagittal DESS sequence (TR/TE = 16.3/4.7, flip angle = 25°) only shows the small subchondral cysts, which are located within the BML depicted in (B). Note that the DESS fails to show the ill-defined hyperintensity representing BML and consequently offers clearer delineation of subchondral cysts than in (B), in which hyperintensity from the cysts is not as clearly differentiated from overlapping ill-defined hyperintensity representing BML. The proximal tibiofibular joint cyst (long gray arrow) seen in (B) is also visualized in (C).

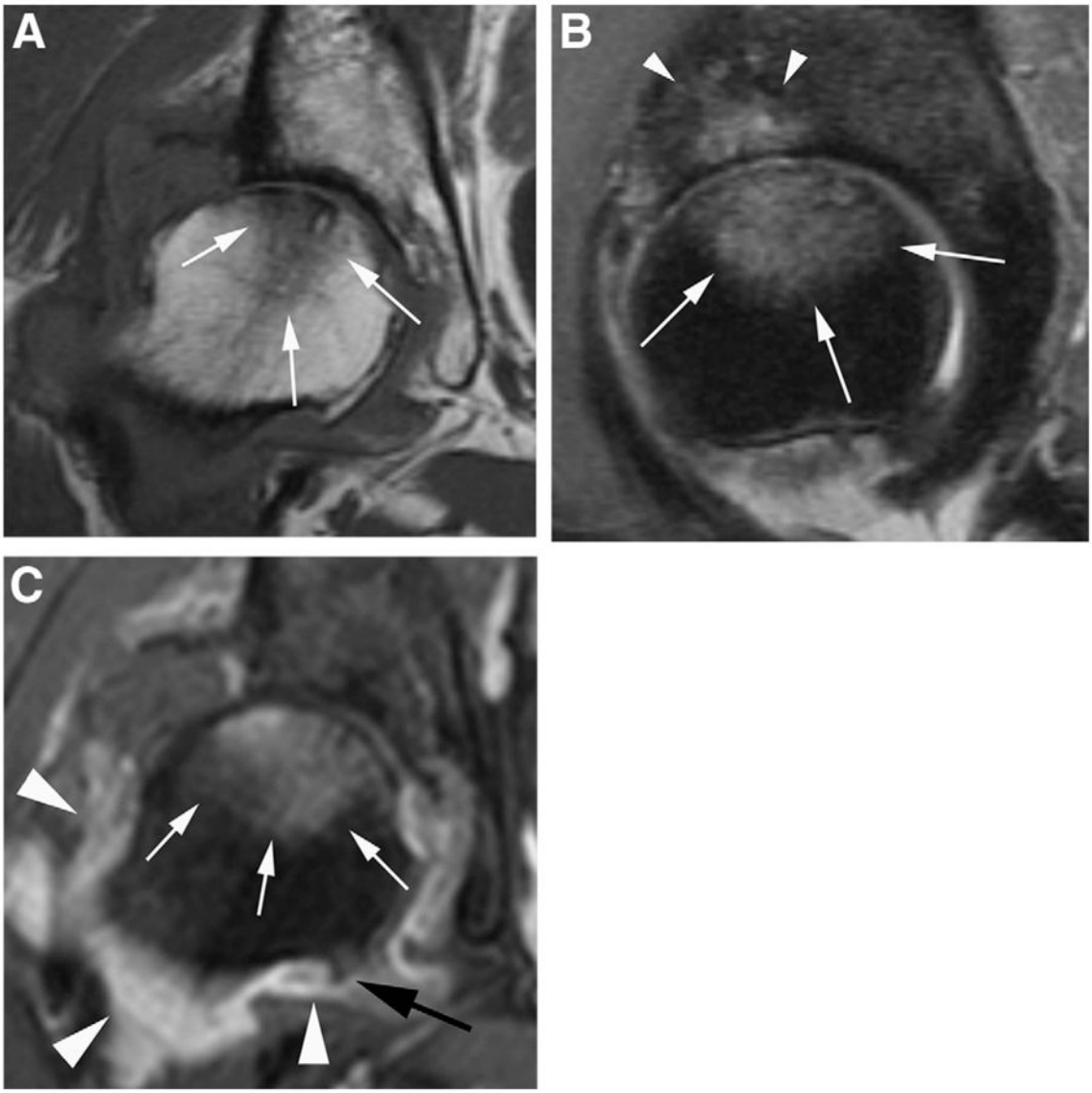

Figure 3.

BMLs in hip osteoarthritis in a 60-year-old woman. (A) Coronal T1-weighted image (TR/TE = 720/15) shows diffuse BML in the central weight-bearing part of the femoral head depicted as hypointensity (white arrows). (B) Sagittal intermediate-weighted fat-suppressed image (TR/TE = 3200/35) shows the same lesion in the femoral head (arrows). A subchondral BML in the weight-bearing part of the acetabulum is also visualized (arrowheads). Note diffuse acetabular and femoral cartilage loss in the central weight-bearing part of the joint (no arrows). (C) Coronal T1-weighted contrast-enhanced sequence (TR/TE = 720/15) shows the same BML in the femoral head depicted with marked enhancement (arrowheads). In addition, there is severe synovitis visualized by marked thickening and enhancement of the synovial tissue (arrowheads). Note small osteophytes at the medial femoral head-neck junction (black arrow).

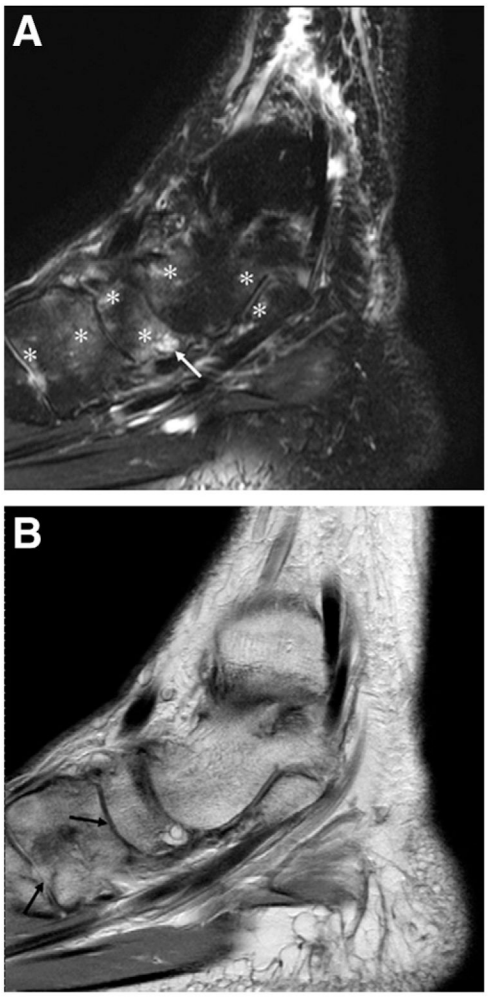

Figure 4.
BMLs in foot osteoarthritis in a 58-year-old man. (A) Sagittal fat-suppressed T2-weighted MRI (TR/TE = 3500/100) shows multiple subchondral BMLs (asterisk) involving the subtalar, talonavicular, cuneonavicular, and tarsometa-tarsal joints. A cystic portion (white arrow) is depicted within the BML in the navicular. (B) Sagittal proton density-weighted MRI (TR/TE = 3500/15) shows diffuse intertarsal cartilage loss (black arrow).

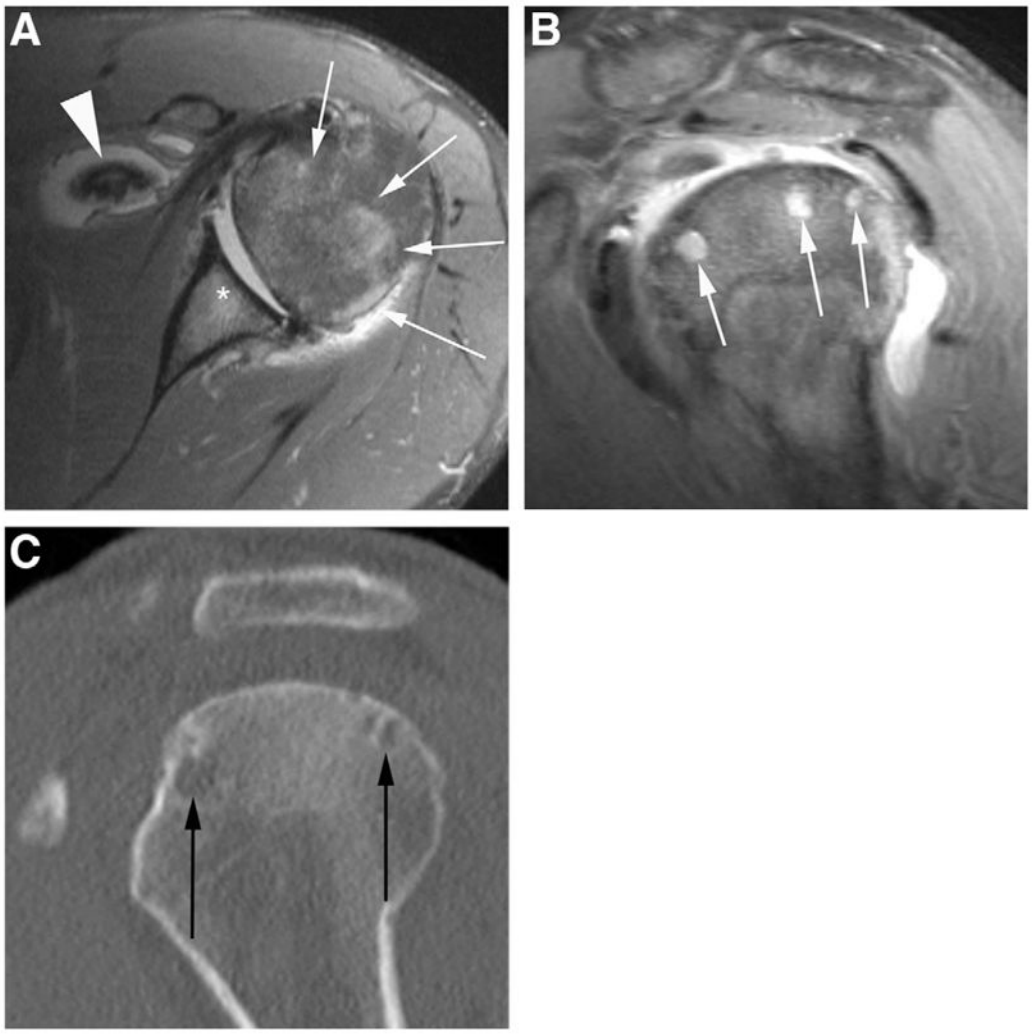

Figure 5.
BMLs of the shoulder OA in a 40-year-old man. (A) Axial intermediate-weighted fat-suppressed image (TR/TE = 3250/55) shows diffuse subchondral hyperintensity in the humeral head reflecting a large BML (arrows). In addition there is a BML in the subchondral glenoid (asterisk). Note an OA-associated large loose body in the anterior recessus subscapularis (arrowhead). Diffuse cartilage loss of the humeral head and the glenoid is depicted (no arrows). (B) Corresponding sagittal MRI (TR/TE = 3850/55) shows cystic lesions within noncystic BML (arrows). (C) Cysts are well depicted by corresponding sagittal CT image (black arrows); however, the poorly defined BML cannot be visualized by CT.

Table 1

Comparison of 4 Different Semiquantitative Scoring Systems for Assessing MRI-detected BMLs in Knee Osteoarthritis

	MRI System	MRI Sequences for Evaluation of BMLs	Subregional Division of Knee	Scoring of BMLs	Reported Interreader Reliability	Reported Intrareader Reliability
WORMS	1.5T	Sag T2w FSE FS	15 subregions: medial/lateral patella, medial/ lateral femur (anterior/central/ posterior), medial/ lateral tibia (anterior/central/ posterior), subspinous tibia	Summed BML size/volume for subregion from 0 to 3 in regard to percentage of subregional bone volume (0 = none; 1 = <25% of the region; 2 = 25 – 50% of the region; 3 = >50% of the region)	ICC 0.74 by Peterfy et al. (2004); w-kappa 0.78–0.94 by Lynch et al. (2010)	Not presented
KOSS	1.5T	Cor/sag PD/ T2w SE, Axial PD/T2wTSE FS	9 subregions: medial patella, patellar crest, lateral patella, medial/lateral trochlea, medial/ lateral femoral condyle, medial/ lateral tibial plateau	Scoring of individual lesions from 0 to 3 concerning maximum diameter of lesion (0 = absent; 1 = minimal, diameter < 5 mm; 2 = moderate, diameter 5 mm to 2 cm; 3 = severe, diameter >2 cm)	ICC 0.76 and w- kappa 0.88 by Kornaat et al. (2005)	ICC 0.92 and w- kappa 0.91 by Kornaat et al. (2005)
BLOKS	1.5T	Sag PD/T2w, cor/axial PD/ T2w FS	9 subregions: medial/lateral patella, medial/ lateral trochlea, medial, lateral weight-bearing femur, medial/lateral weight- bearing tibia, subspinous tibia	Scoring of individual lesions for 3 aspects of BMLs: a. Size of BML scored from 0 to 3 concerning % of subregional bone volume (0 = none; 1 = <10% of the region; 2 = 10 – 25%; 3 = >25%); b. % of surface area adjacent To subchondral plate (0 = none; 1 = <10% of surface area; 2 = 10 – 25%; 3 = >25%); c. % of BML that is noncystic (0 = none; 1 = <10% of the lesion; 2 = 10 – 85% of the lesion; 3 = >85% of the lesion)	w-kappa 0.69–0.72 by Hunter et al. (2008); w-kappa 0.74–0.92 by Lynch et al. (2010)	Not presented
MOAKS	3T	Axial/cor/sag PD/Iw/T2w TSE FS	15 subregions: medial/lateral patella, medial/ lateral femur (trochlea/central/ posterior), medial/ lateral tibia (anterior/central/ posterior), subspinous tibia	Scoring of the entire subregion for BMLs in 3 different aspects: a. Number of lesions in each subregion; b. Summed BML volume for subregion from 0 to 3 in regard to % of subregion bone volume (0 = none; 1 = <33% of the region; 2 = 33% to 66% of the region; 3 = >66% of the region); c. % of BML that is noncystic (0 = none; 1 = <33% of the lesion; 2 = 33% to 66% of the lesion; 3 = >66% of the lesion)	w-kappa 0.65–1.0 by Hunter et al. (2011)	w-kappa 0.50–1.0 by Hunter et al. (2011)

BLOKS, Boston-Leeds Osteoarthritis Knee Score; BML, bone marrow lesion; cor, coronal; ICC, intraclass correlation coefficient; KOSS, Knee Osteoarthritis Scoring System; MOAKS, Magnetic Resonance Imaging Osteoarthritis Knee Score; PD, proton density; sag, sagittal; T2w FS, T2-weighted fat-suppressed sequence; T2w FSE FS, T2-weighted fast spin echo fat-suppressed sequence; T2w SE, T2-weighted spin echo sequence; T2w TSE FS, T2-weighted turbo spin echo fat-suppressed sequence; w-kappa, weighted kappa; WORMS, Whole Organ Magnetic Imaging Score.