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REVIEW

Mechanism of traumatic knee injuries and MRI findings

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Abstract Bone bruises are focal abnormalities in subchondral bone marrow due to trabecular microfractures as a result of traumatic force. These trauma-induced lesions are better detected with magnetic resonance (MR) imaging using water-sensitive sequences. Moreover, the pattern of bone bruise is distinctive and allows us to understand the dynamics of trauma and to predict associated soft injuries. This article discusses the mechanism of traumatic injury and MR findings.

Keywords Bone bruise · Traumatic knee injuries · Magnetic resonance imaging

Introduction

Traumatic knee injuries result from forces producing an impaction lesion at the entry site of the force and a distraction injury, or avulsion, at the opposite site of the force. Moreover, these forces produce not only bone contusions but also soft tissue injuries [1]. When these findings are not well defined, the presence of associated subcutaneous hematoma and/or muscle lesions might help in comprehending the global picture of knee injuries. It is recognized that the ability to define the mechanism of injury has both clinical and forensic implications.

The bone bruise or bone contusion are commonly used to define an occult bone alteration edematous-hemorrhagic due to trabecular microfractures as a result of a direct blow to the bone, application of compressive forces on contiguous bones with a consequent impact mechanism, and the action of a torsional force, and to stresses by traction on the subchondral bone by insertion of the ligament, tendon or capsular as occurs in trauma avulsion. Although in the literature bone bruise has been described in trauma of different articular districts [2–4], the vast majority of the articles refer to knee joint.

Plain radiographs are insensitive for detecting trabecular injuries because the overlying cortex is often intact.

Magnetic resonance (MR) is better than conventional radiographs, ultrasound, computed tomography and also arthroscopy to describe bone bruises and associated soft tissues injuries [5–15].

In fact, MR only has the ability to identify a bone bruise and to characterize, using different sequences, the entire spectrum of alterations referable to the medullary bone bruise including bleeding, hemorrhage and edema [16–19]. Subchondral bone marrow edema-like signal alterations exhibit typical signal characteristics on MRI and are common but nonspecific findings. Bone bruise demonstrates ill-defined low signal intensity on T1-weighted images and increased signal intensity on T2-weighted or proton density-weighted fat-suppressed (FS) fast spin-echo (FSE) or short tau inversion recovery (STIR) images where standard radiographs showed nonspecific osteopenia or normal findings [20]. These lesions range in size over time and regress spontaneously from 3 weeks to 2 years but may have deleterious effect on the overlying articular cartilage evolving in articular cartilage degeneration [21, 22].

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The distribution of bone marrow edema is like a footprint of the mechanism of injury and therefore allows us to understand the dynamics of trauma and to predict with a high accuracy rate of the associated soft tissue injuries [23, 24]. To trace the mechanism of insult, the various classification systems consider knee position, acting forces, bone bruise patterns and related soft tissue injury. Furthermore, MR results in the method of choice for the differentiation of the bone marrow edema resulting from trauma from other bone marrow edema syndrome secondary to infections, degenerative arthritis, cancer, osteoporosis and transient in the early stages of avascular necrosis [13, 22–34].

We reviewed the current scientific literature to point out the elective role of MR imaging in the detection of bone marrow lesions occurring in traumatic events (mainly in patients without radiographic evidence of fracture) and the ability of the information resulting from bone bruise pattern to identify the forces acting on the knee [35].

Technical note and MRI imaging findings of bone bruise

The MR features of bone bruising reflect the increase in water content of the marrow cavity as a result of hemorrhage; therefore, research groups in the radiological community have been applying water-sensitive sequences such as fat sat T2-weighted, PD-weighted or STIR scans [13, 36–40].

PD–FSE fat sat sequences are more sensitive in the detection of bone contusions than PD–FSE and FSE T2-weighted sequences.

PD-weighted sequences are useful to differentiate bone contusion, as areas of increased signal intensity, from subchondral sclerosis, which demonstrates decreased signal intensity. Moreover, assessment of other structures in the knee with PD–FSE fat sat provides a better spatial resolution than the more heavily T2-weighted FSE fat sat and inversion recovery sequences [41].

Gradient-recalled echo (GRE)-type sequences, even with robust fat suppression or water excitation, are insensitive to diffuse marrow abnormalities because of trabecular magnetic susceptibility and will not show the full extent of this lesion [42–44].

Yao and Lee were the first to describe a series of eight patients with acute knee injury and with normal radiographs but in whom MR showed irregular foci of increased signal on T2-W and low signal on T1-W spin-echo (SE) images [45].

Mink was the first to identify bone bruising as a distinct entity in 1987 [46], and with Deutsch [47] in 1989, they were the first to classify bone bruises. They separated these lesions into four groups: bone bruises, stress fractures, femoral and tibial fractures and osteochondral fractures. The first two groups were classified solely on history since their appearance on MR imaging is similar. The later two groups were found to have the characteristic MR findings of a bone bruise and the fractures for which they were classified.

Lynch et al. [48] in 1989 divided the lesion into types one, two and three depending on the morphological criteria. Type I is diffuse often reticulated signal intensity loss in the metaphyseal and epiphyseal regions on short TE SE images and increased signal on T2-W images. Type II lesions are similar to type I lesions but associated with an interruption in the smooth cortical line. Type III lesions are defined as a profound signal intensity loss primarily restricted to the immediate subcortical region, seen on short TE images.

Vellet et al. [49] defined occult fractures as areas of diminished signal intensity on T1-W images and of increased signal intensity on T2-W and T2* images and classified these occult fractures into reticular, geographic, linear, impaction and osteochondral fractures. Recticular occult subcortical fractures are represented by regions of reticular, serpiginous stranding of diminished signal intensity on T1-W images within the high signal intensity of the epiphyseal or metaphyseal marrow. These lesions show variable degrees of coalescence within the marrow compartment but are distant from the cortical bone of the subjacent articular surface.

Geographic occult subcortical fractures are characterized by their contiguity to the subjacent cortical bone, which may demonstrate focal cortical impaction. They are further subdivided into two subgroups depending upon the presence or absence of peripheral reticulation. Higher grades or such lesion are similar in appearance to in situ osteochondral fractures.

Linear occult subcortical fractures are discrete linear regions of diminished signal intensity on T1-W images. These lesions are usually less than 2 mm width, without evidence of significant reticulation.

Impaction fractures occur in conjunction with geographic or, less often, reticular fractures. They demonstrate variable degrees of depression of the articular cortical osteochondral surface. Discrete disruption of the cortical bone may not be apparent in the site of the impaction although it may be of increased signal intensity with all pull sequences.

Osteochondral fractures may be either occult or overt lesions and are identified as discrete adherent or distracted cortical fractures associated with variable quantities of marrow fat.

Currently, the available classification systems contribute little toward understanding the underlying pathology of the bone bruising, but there is controversial evidence regarding the prognostic significance of the different types of bone bruise.

Bondhorf [50] in 1999 released a new classification merging various findings at direct inspection (arthrotomy and arthroscopy) and the aspects of acute articular surface lesions evaluated with MRI.

Bone contusions related to the mechanism of knee injury

Bone bruise location reflects the mechanism of injury. Generally, forces acting on the knee produce an impaction injury at the site of force and a distraction injury at the opposite, or exit, site of the force.

A comprehensive classification system based on the mechanisms of injury would be useful because an understanding of causative mechanism may improve the detection of the complete constellation of injuries and appreciation of the mechanism of injury may help to predict both immediate and delayed instability and need for surgery [1].

Various classification systems based on the mechanisms of injury are available in the literature. Sanders et al. [25] in 2000 described five contusion patterns with associated soft injuries: pivot shift injury, dashboard injury, hyperextension injury, clip injury and lateral patellar dislocation.

The pivot shift injury occurs when a valgus load is applied to the knee in various states of flexion combined with external rotation of the tibia or internal rotation of the femur and will result in disruption of anterior cruciate ligament (ACL).

The resulting bone contusion pattern will be present in the posterior aspect of the lateral tibial plateau and mid-portion of the lateral femoral condyle near the condylopatellar sulcus (Fig. 1).

Kaplan described another bone contusion pattern associated with the pivot shift involving the posterior lip of the medial tibial plateau resulting from countercoup forces in the medial compartment [51].

Sometimes, this mechanism of injury involves other soft tissue structures like tears/posterior capsule and arcuate ligament, medial collateral ligament (MCL) and the menisci [25].

Dashboard injury occurs when force is applied to the anterior aspect of the proximal tibia while the knee is in a flexed position. This injury typically occurs when the knee strikes against the dashboard during a vehicle accident.

The bone bruise distribution includes the anterior aspect of the tibia and the posterior surface of the patella. The structural abnormalities expected with this mechanism of injury include disruption of posterior cruciate ligament (PCL) and posterior joint capsule.

Hyperextension of the knee can result when direct force is applied to the anterior tibia while the foot is planted or from an indirect force resulting in a kissing contusion pattern in the anterior aspect of the distal femur and proximal tibia (Fig. 2). ACL, PCL or menisci may be involved depending on the amount of force applied.

The clip injury is a contact injury that occurs after a pure valgus stress is applied to the knee while the knee is in a state of mild flexion involving MCL. Bruising is usually found in the lateral femoral condyle secondary to the direct blow. Moreover, a second smaller area of edema may be present in the medial femoral condyle secondary to avulsion stress to MCL.

Transient dislocation of the patella results from a twisting motion of the knee especially while knee is in a state of flexion [52]. The classic bone contusion pattern seen after lateral patellar dislocation includes involvement of the inferomedial aspect of the patella and anterolateral aspect of the lateral femoral condyle [53, 54]. This bone contusion pattern is located more anteriorly and peripherally than the bone bruise associated with pivot shift injury.

In the same year, Hayes et al. [1] published a mechanism classification system based on the patterns of bone marrow edema and ligament injury for complex knee injuries shown at MR imaging. The classification system takes into account knee position, forces and recognition of patterns of bone injury with complementary soft tissue injury subdivided into ten categories, according to the knee position (flexion, extension), direction of force and presence or absence of rotation.

Hyperextension injuries are subdivided into pure hyperextension, hyperextension with varus, which is the most common type, and hyperextension with valgus. These injuries by virtue of the greater forces exerted on the extended or "locked" knee produce more pronounced bone injury patterns, often with frank fractures. Severe distraction injuries on the posterior exit side of the joint are common with this pattern. These injuries are particularly serious since they involve the critical posteromedial and/or posterolateral corners of the knee.

In pure hyperextension mechanism, bone bruise will be located in anterior central tibia and anterior femoral condyles (impactions). In the hyperextension with varus mechanism, the bone contusion pattern involves the anteromedial tibia, femoral condyle (impactions), posterolateral corner and proximal fibula (avulsion) (Figs. 3, 4), while in the hyperextension with valgus, bone marrow edema is usually most prominent in anterolateral tibia, femoral condyle (impactions) and posteromedial tibia (avulsion).

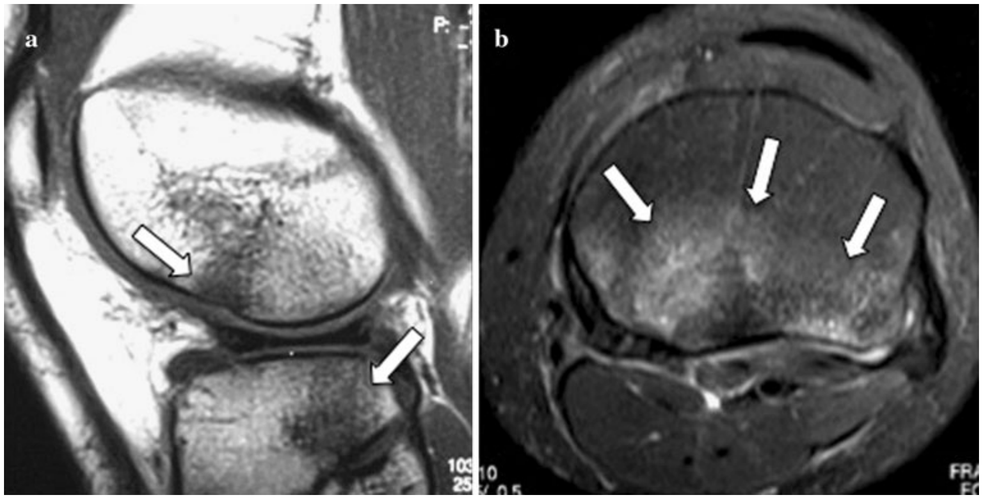

Fig. 1 Forces that adduct and internally rotate the tibia. **a** Sagittal PD and **b** axial PD fat sat images demonstrate that bone marrow edema pattern (*arrows*) involves the lateral condylar notch and the posterior tibial plateau

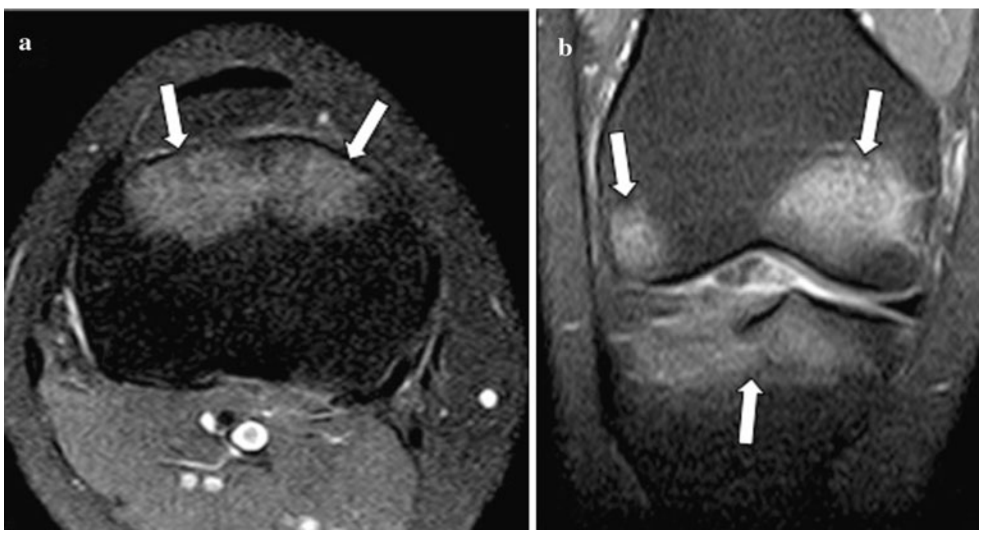

Fig. 2 Pure hyperextension injury. **a** Axial and **b** coronal PD fat sat images show bone bruise pattern involving the anterior aspect of the femoral condyles and anterior tibial plateau ("kissing contusions")

Flexion injuries include the following: flexion valgus with external rotation mechanism (Fig. 5); flexion varus with internal rotation; and the flexion with posterior tibial translation mechanism, which is the most frequent type. These mechanisms of injuries tend to show few contiguous impaction bone injuries but have a greater tendency to produce injury due to internal or external rotation. Non-contiguous impaction bone bruises are usually found, as well as smaller avulsion bone bruises. In the flexion valgus with external rotation, the pattern involves lateral femoral condyle, posterolateral tibia (impaction), posteromedial tibia and femoral condyle (avulsion vs. countercoup). Flexion varus external rotation results in bone contusion pattern in the lateral femoral condyle, posterolateral tibia (ACL tear-related impaction), posterolateral tibia (Segond avulsion) and fibular head (avulsion). Bone bruise is not observed in flexion posterior tibial translation only associated with isolated PCL disruption. Pure valgus and the rare pure varus categories are characterized by a simple "coup–countercoup" pattern of impaction bone injuries involving lateral structures of the knee in pure valgus and medial structures in the pure varus. Opposite sided distraction ligament in injuries depending on the severity of the force. Dislocation of the patella is typically produced by combined flexion, valgus and internal rotation of the femur on a fixed tibia. This mechanism of injury is very similar to flexion, valgus and external rotation (tibia on fixed femur), although they were separated in two different categories on the basis of their different injury patterns. In this case, the bone bruise involves medial patella and

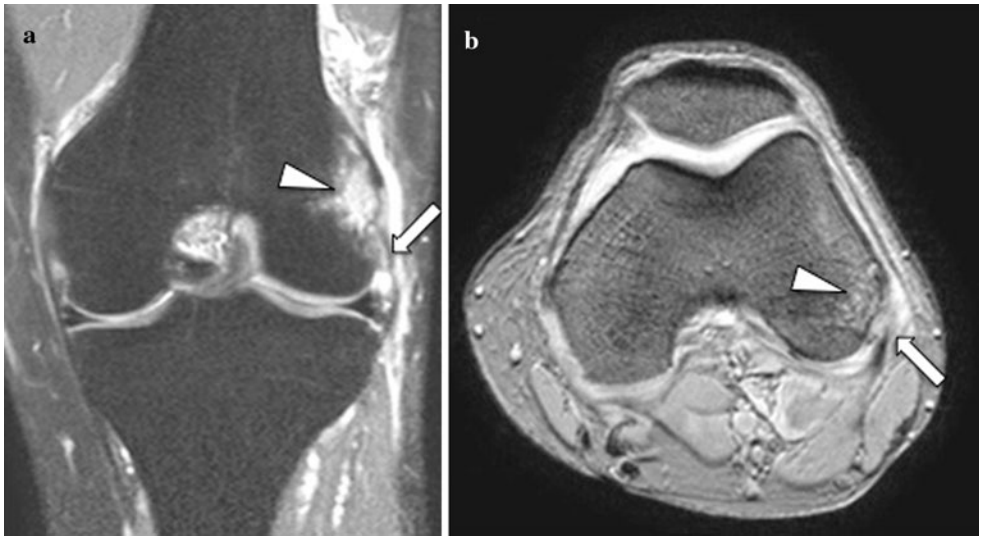

Fig. 3 Hyperextension with varus. **a** Coronal PD fat sat image shows bone bruise (*arrowhead*) concentrated in the lateral femoral condyle with abnormal signal intensity of the MCL (*arrow*). **b** Axial GRE T2* image shows bone marrow edema pattern in the lateral femoral condyle due to avulsion injury (*arrowhead*) with abnormal high signal intensity of the soft tissue in the posterolateral knee (*arrow*)

Fig. 4 Hyperextension with varus. Sagittal PD fat sat image demonstrates disruption of the lateral head of gastrocnemius (*arrow*) and popliteus tendons (*arrowhead*)

lateral condyle (impaction). Broad bone contusions located beneath the site of impaction characterize direct trauma (Fig. 6). Typically, there are no injuries on the opposite side of the knee. Direct anterior trauma, which causes patellar and trochlear groove contusions, and lateral or medial blows are most common (Fig. 7).

In 2002, Chung et al. [55] starting from physical examination findings, presented a comprehensive classification system of complex knee injuries based on instability pattern. The resultant system includes straight, rotational and combined types of knee instability (Table 1).

Combined instability patterns are the result of such complex injuries that both clinical and imaging findings could be difficult to interpret.

Natural history and clinical significance

The natural history of bone bruises has not been fully elucidated although the outcome could be related to the extent and location of the lesion.

Resolution time of bone bruising diversifies in the various studies, from 3 weeks to 2 years. This feature could derive from severity of injuries and any related soft tissue abnormalities as the extent of bone bruising.

Wright et al. [56] in 2000 studied the clinical outcome of isolated bone bruising. They reported that the average time to return to preinjury activity level was 3.2 months, with 91 % of the group returning at 6 months or less, and the time to return to activity was not dependent on the Vellet classification of bone bruise type.

Breatlau [16] studied 16 patients. At the early follow-up 4 months after trauma in 5/16 patients (31 %), bone bruise had resolved. In the remaining 11 patients (69 %), the bone bruise was more diffuse but less intense. At the late follow-up after approximately 12 months, the bone bruise had resolved in 22 of 25 patients (88 %), while in 3 patients (12 %), bone bruise was still detectable but was more diffuse and less intense than at the early follow-up.

Contrary to Miller [57] study, who reported resolution of bone bruises in all patients with isolated MCL injuries, two

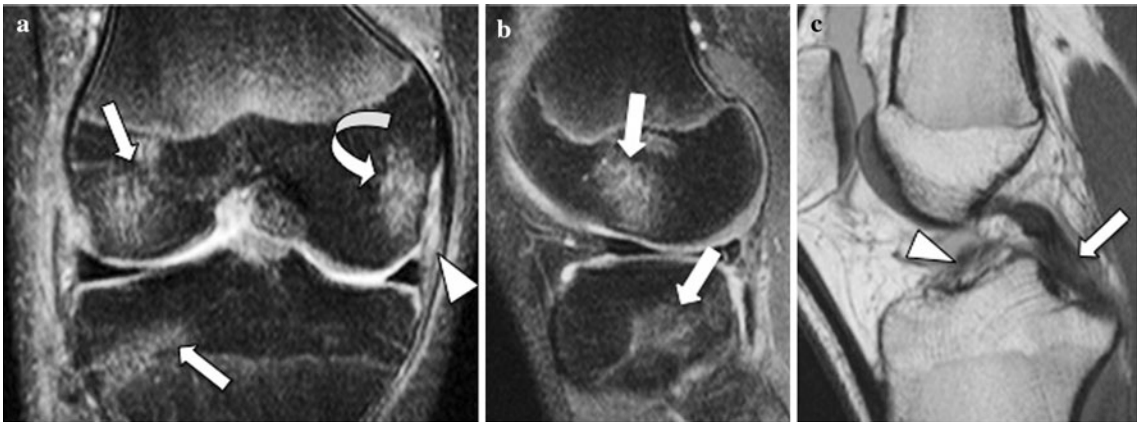

Fig. 5 Flexion valgus with external rotation injury. **a** Coronal and **b** sagittal PD fat sat images show impaction bone marrow edema involving lateral femoral condyle and lateral tibial plateau (*arrows*). MCL distraction (*arrowhead*) with bone marrow edema from avulsion injury of the medial femoral condyle (*curved arrow*). **c** Sagittal PD image shows ACL disruption (*arrowhead*) and high intensity signal of the PCL (*arrow*)

Fig. 6 Direct trauma. **a** Sagittal PD fat sat image demonstrates bone marrow edema at the point of impact on the anterior aspect of the tibial plateau (*arrowhead*). The ACL is intact indicating an injury of mild to moderate severity. **b** Sagittal PD fat sat image shows bone bruise of the anterior tibial (*arrowhead*) with disruption of the ACL (*arrow*) suggesting a severe force impaction type

studies have demonstrated the persistence of bone bruise in the 10–15 % of the patients in a 2-year follow-up MR findings [58, 59].

As reported, bone bruise is often associated with occult subcortical fractures.

Vellet et al. [49] described, at 2-year follow-up MR imaging, the evidence of osteochondral sequelae corresponding anatomically to the site of their geographic fractures in the 67 % of patients and 16–69 % in the lateral femoral condyle bone bruise. Resolution with no apparent sequelae at the site of the associated reticular fracture was demonstrated in 100 % of cases.

Roemer [59] retrospectively looked at long-term osseous sequelae after acute trauma of the knee joint evaluated by MR. They found a prevalence of bone bruise of 72 % in 176 patients: 35 patients had isolated bone bruising. After a minimum of 2 years, they evaluated 49 patients with MR and concluded that acute posttraumatic bone bruising vanished in the majority of patients after 2 years.

Osteochondral changes include cartilage thinning, subcortical sclerosis, osteochondral defects and cortical impaction [49].

No significant correlation was found between the location of a bone bruise on MR and the articular cartilage change [47]. Outcome would be caused by a complex interaction of loading dynamics such as force, duration, direction, elasticity of subchondral bone and cartilage, cartilage volume, and integrity of transcortical cartilage vascularity [48, 60].

In the literature, bone bruise is common in uncomplicated injuries and has minor, if any, clinical significance. In 1996, Schweitzer and Lawrence [3] demonstrated that altered biomechanics can result in bone marrow edema and these MR changes may represent the conjectured "stress

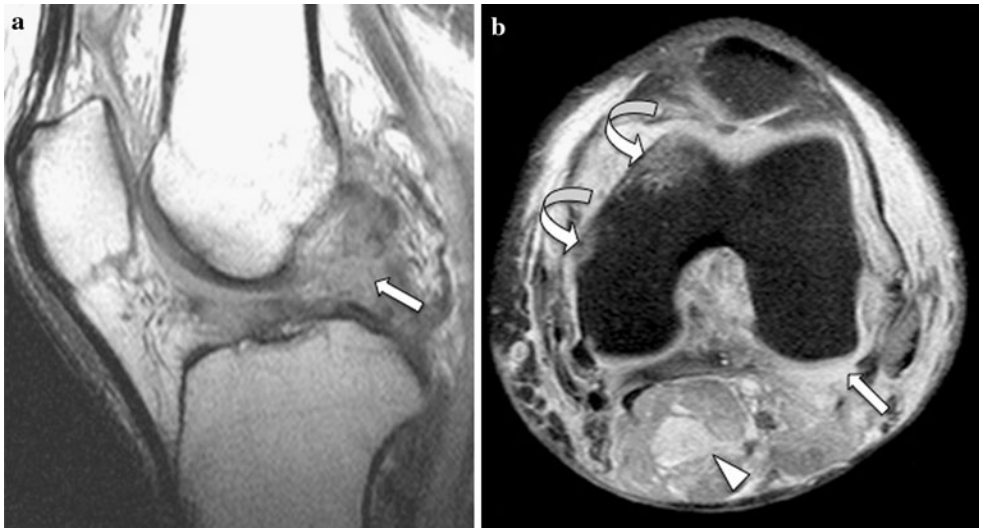

Fig. 7 Knee injury produced by a severe force applied to the medial aspect of the joint. **a** Sagittal PD TSE shows ACL and PCL disruptions (*arrow*). **b** Axial PD fat sat image demonstrates bone contusion in anterior aspect of the medial femoral condyle (*curved arrows*) with structural abnormalities of the posterolateral soft tissue (*arrow*) and intramuscular fluid collection of gastrocnemius (*arrowhead*)

Table 1 Bone bruise's distribution and associated injuries according to traumatic mechanism

Mechanism	Bone bruise	Associated injury
One plane, medial instability and valgus force on the lateral aspect of the knee	Lateral femoral condyle	Medial supporting structures
One plane, lateral instability and varus force on the medial aspect of the knee (Fig. 7)	Medial femoral condyle and medial aspect of the tibia	Lateral supporting structures
One plane, posterior instability, direct force applied below the patellar tendon or hyperextension and hyperflexion of the knee	Femoral condyle, anterior aspect tibia, articular surface and patella	Posterior cruciate ligament (PCL)
One plane, anterior instability, force applied to the posterior aspect of the leg	Anterior femoral condyles and tibia	Anterior cruciate ligament (ACL)
Anteromedial rotary instability, valgus and external rotation forces applied to the flexed knee	Medial and lateral femoral condyles, posteromedial and posterolateral of the tibia	Anterior cruciate ligament and medial supporting soft tissues
Anterolateral rotary instability, forces that adduct and internally rotate tibia with respect to the femur	Lateral femoral condyle and posterolateral aspect tibia	Partial or complete disruption of the ACL
Posterolateral rotary instability, force applied to an extended knee that drives the tibia, in neutral position or internal rotation forward on the femur	Anterior aspect of the medial femoral condyle and anteromedial aspect of the tibia	Posterior cruciate ligament, popliteus tendon, arcuate ligament complex and lateral capsular ligament
Posteromedial rotary, the existence is controversial	Anterolateral femoral condyle and anterolateral aspect of the tibia articular surface	Medial collateral ligament, medial capsular ligament, posterior oblique ligament and medial portion posterior capsule

response" or subclinical fracture. Although these changes can be painful, all volunteers in their study were asymptomatic. In a similar manner, study of Lazzarini et al. [2] has demonstrated that running can result in bone marrow edema in the absence of clinical symptoms or pathological abnormalities. Although bone bruises are often regarded as benign and self-limiting lesions, the importance of their detection is highlighted by study findings suggesting that severe bone bruises can be a precursor of early degenerative changes, even in the absence of other substantial soft tissue trauma [61]. Faber et al. [62] demonstrated that no clinical differences could be detected between cases where follow-up MR showed subchondral or cartilage injuries and those where follow-up MR showed no injuries.

Conclusion

Nowadays, the role of the radiologist cannot be limited to the description of the image findings, but he must provide information that will improve the clinical picture of the patient. The bone marrow edema is like a footprint of mechanism injury, and its location allows realizing the traumatic mechanism. Moreover, it is a self-limiting disorder that resolves in most cases 4–12 months after injury, especially in patients with knee injury with no abnormalities seen on conventional radiographs. When bone bruise is associated with subchondral or osteochondral injuries it may have deleterious effect producing late cartilage degenerative changes due to decreased compliance of the subchondral bone.

Therefore, even if the detection of bone marrow edema has not prime clinical significance, its importance lies in the ability to predict both underlying soft tissue injuries and long-term degenerative changes and in guiding rehabilitative management (such as nonweight bearing in the initial part of the treatment). Also, it is important to differentiate bone bruise, observed in conjunction with trauma, from bone marrow edema related to other pathologies such as avascular necrosis, inflammatory, osteoarthritis, tumor and malignant infiltration or idiopathic transient bone marrow edema syndrome [13].

Conflict of interest P. Ciuffreda, M. Lelario, P. Milillo, R. Vinci, F. Coppolino, L. P. Stoppino, E.A. Genovese and L. Macarini declare that they have no conflict of interest.

Ethical standard The study described in this article did not include any procedures involving humans or animal.

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