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Original Article

Grade of Subchondral Insufficiency Fracture of the Knee and the Presence of a Posterior Shiny-Corner Lesion are Correlated with Duration of Medial Meniscus Posterior Root Tear in Women

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Bone marrow edema (BME) after meniscus injury and risk factors for subchondral insufficiency fracture of the knee (SIFK) have been reported. However, their association with medial meniscus posterior root tear (MMPRT) remains unknown. We investigated the association of BME volume (BME-V), posterior shiny-corner lesion (PSCL), and SIFK with MMPRT to examine the correlations between BME-V and medial meniscus extrusion (MME), PSCL and duration from injury to the time of magnetic resonance imaging (duration), and SIFK and duration. Twenty-nine patients who underwent surgery for MMPRT were included (mean age, 59.2; range, 39-84). The presence of PSCL, femoral BME-V (cm^3), and SIFK grade (1-4) were evaluated. Preoperative factors, such as MME (mm) and duration (weeks), were investigated using multivariate linear/logistic regression analyses. Multivariate linear regression analysis revealed duration as a significant factor for high-grade SIFK ($p < 0.01$). Multivariate logistic regression analysis revealed duration as a significant factor for the presence of PSCL (odds ratio = 0.94, $p < 0.05$). A long duration of MMPRT leads to severe MME and high-grade SIFK (3 and 4), often resulting in knee arthroplasty. Early diagnosis of MMPRT and pullout repair can prevent severe MME and high-grade SIFK.

Key words: medial meniscus, posterior root tear, subchondral insufficiency fracture, bone marrow edema, meniscus extrusion

Bone marrow edema (BME) after meniscus injury or knee osteoarthritis (OA) has been reported, and a posterior shiny-corner lesion (PSCL) of the tibia is often seen on magnetic resonance imaging (MRI) following medial meniscus posterior root tear (MMPRT) [1-6]. Subchondral insufficiency fracture of the knee (SIFK) is a subchondral plate fracture surrounded by perifocal “flame-like” marrow edema that can extend along and beyond the adjacent epiphysis [7]. A grading system (1-4) of SIFK has also been reported, along with its risk factors and outcomes [8]. Mechanical knee malalignment and high compartmental loads and structural lesions, including meniscal pathologies, are risk factors for cartilage injury and BME in the knee joint [4,6]. Furthermore, meniscus pathology or derangement, medial meniscus extrusion (MME) and BME correlate with progressive knee OA [3,9]. Given the role of BME in the pathogenesis of knee OA, strategies to modify these risk factors are important for reducing the burden of the knee and slowing the progression of knee OA in those incurring

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MMPRT [4].

Many clinical and biomechanical studies on MMPRT have been conducted. Biomechanical changes after MMPRT are similar to those after meniscectomy, and good clinical outcomes have been reported after repair surgery; conservative treatment has shown worse clinical outcomes and can also lead to knee arthroplasty. Nevertheless, only a few studies have reported associations among demographic data in patients undergoing surgery for MMPRT and BME, PSCL, or SIFK [1,5,8,10]. Furthermore, these associations have not been fully elucidated. Therefore, the aim of this study was to measure correlations among preoperative factors, including age, body mass index (BMI), femorotibial angle (FTA), MME, duration from injury to the time of MRI (duration), and clinical evaluations, including the volume of BME, presence of PSCL, and SIFK grade [8]. We hypothesized that MME positively correlates with BME and that duration negatively correlates with PSCL and positively correlates with SIFK grade in the MMPRT knee.

Materials and Methods

Patients and ethical considerations. Forty-two consecutive patients who underwent surgery for MMPRT between January 2016 and May 2019 at our hospital were retrospectively evaluated. Of the 42 patients, 13 were excluded because they were men and the bone quality of men is considered to be different [11], and because they had an unclear painful popping episode, history of surgery on the same side, or unavailable MRI data. Total knee arthroplasty (TKA) was performed for patients who had severe bilateral compartment and patellofemoral OA changes (Fig. 1), and medial uni-compartmental knee arthroplasty (UKA) was performed for patients who had only medial compartment OA changes with severe cartilage damage. Pullout repair was performed for patients who had mild OA changes without severe cartilage damage (Fig. 2). The patient in Fig. 1 underwent TKA because she had severe OA change (Kellgren-Lawrence grade 3) and high-grade SIFK (grade 3), whereas the patient in Fig. 2 underwent pullout repair because she had mild OA change (Kellgren-Lawrence grade 1) and low-grade SIFK (grade 2). Among 29 patients, 7 (24%) under-

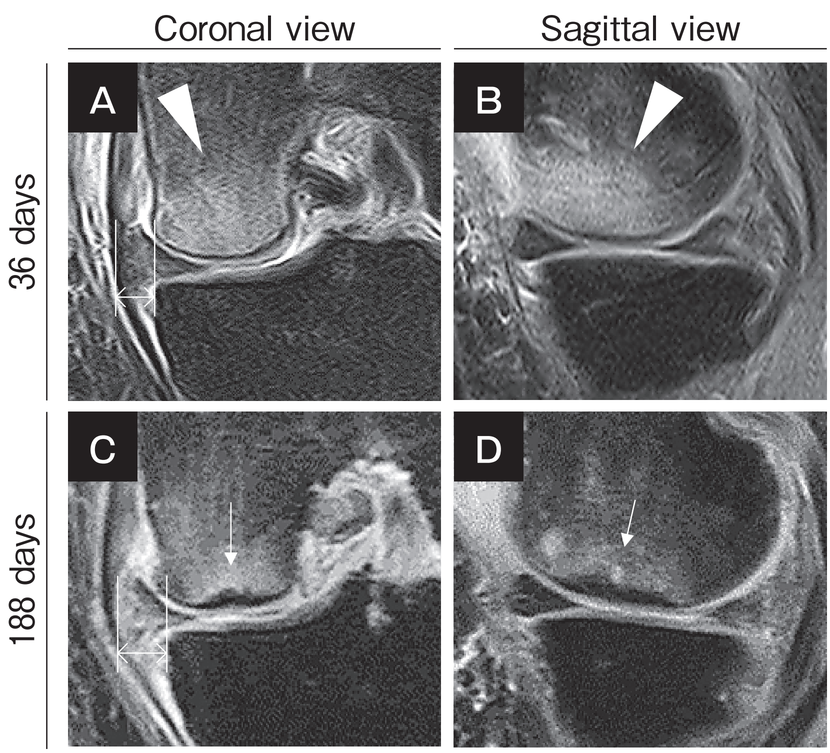

Fig. 1 MRI of patients who underwent total knee arthroplasty. (**A**, **B**) Images 36 days after MMPRT showing SIFK grade 1 (arrowhead) and severe MME (5.5 mm). (**C**, **D**) Images 188 days after MMPRT showing SIFK grade 3 (arrow) and MME progression (7.1 mm).
MRI, magnetic resonance imaging: MMPRT, medial meniscus posterior root tear; SIFK, subchondral insufficiency fracture of the knee.

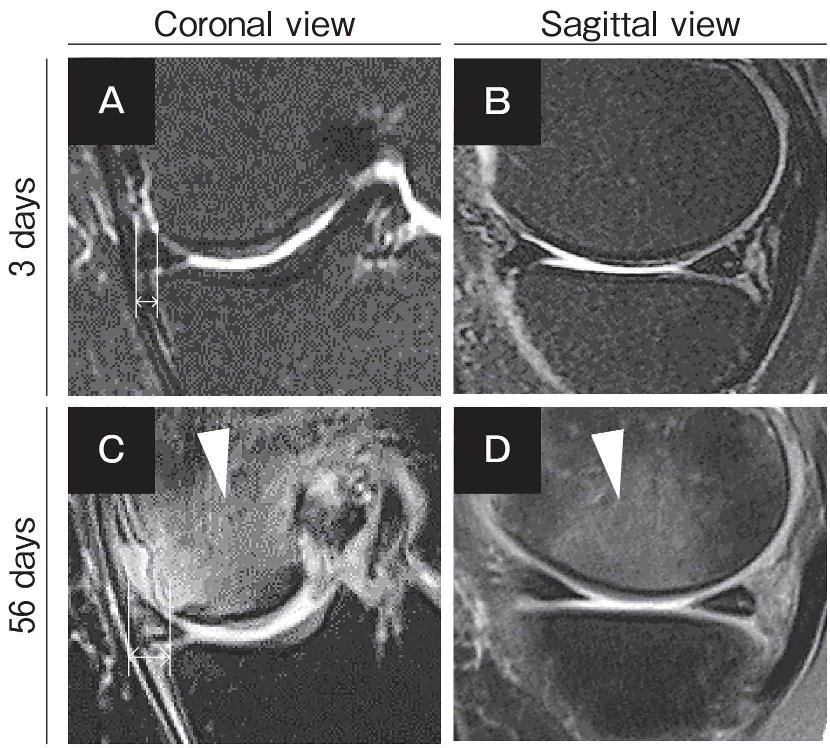

Fig. 2 MRI of patients who underwent MMPRT repair. (A, B) Images 3 days after MMPRT with no apparent BME and moderate MME (3.6 mm). (C, D) Images 56 days after MMPRT with outstanding BME (arrowhead) and MME progression (5.1 mm).
MRI, magnetic resonance imaging; MMPRT, medial meniscus posterior root tear; BME, bone marrow edema; MME, medial meniscus extrusion.

went TKA, 4 (14%) underwent UKA, and 18 (62%) underwent transtibial pullout repair. Medical records were reviewed retrospectively to examine age, height, body weight, and MRI.

All patients were diagnosed with MMPRT based on MRI findings, such as cleft sign, giraffe neck sign, ghost sign, radial tear, and meniscal extrusion [12, 13]. Femoral BME volume (BME-V) (cm^3), presence of PSCL, and SIFK grade were evaluated. This study, and all protocols, were approved by our institutional review board (#1857), and informed consent was obtained from all individual participants included in the study.

Assessment of BME, PSCL, and SIFK. Imaging evaluation was performed using a MAGNETOM Verio 3 T (Siemens AG, Munich, Germany) with a coil. Standard sequences included sagittal/coronal (TR/TE 3,500/61) and axial T2-weighted fat suppression (TR/TE 3,700/61) with a 120° FA. Slice thickness was 3 mm with a 0.6-mm gap. The field of view was 16×16 cm with an acquisition matrix size of 512×410.

Femoral BME lesional elliptical volume (cm^3) was calculated by measuring the anteroposterior (AP; in the sagittal plane), transverse (TR; in the coronal plane), and craniocaudal (CC; in the coronal plane) dimensions using the following formula: volume $= 4/3 \times (\pi abc)$, where a = AP dimension, b = TR dimension, and c = CC dimension (cm) [14].

Subchondral fractures were defined as T1-T2 hypointense signal intensity changes, usually as a line paralleling the articular surface, as previously described [8]. Grades 1 and 2 were considered low-grade lesions, and grades 3 and 4 were considered high-grade lesions. A shiny-corner lesion was defined as a focal, peripheral hyperintense lesion at the superior aspect of the medial tibial plateau, corresponding to the meniscal-covered regions. Cyst-like lesions and marrow alteration immediately deep to the root ligament entheses were not included according to the original report [1], because subcortical cysts are associated with ligament or meniscal pathologies [15].

MRI were evaluated by two experienced orthopaedic surgeons (with 7 and 11 years of experience in performing radiologic interpretation, respectively, including MRI and surgical treatment of patients); they independently performed each evaluation in a blinded manner. Each observer performed each evaluation twice, at least 2 weeks apart. When the assessments were inconsistent, the most experienced surgeon in the operation team assessed the findings with a spot consultation.

Inter- and intra-observer reliabilities were assessed by calculating the intra-class correlation coefficients (ICCs). An ICC > 0.80 was considered to represent a reliable measurement. The ICCs for intra- and inter-observer reliability for MME/BME-V measurements were 0.91/0.87 and 0.9/0.83, respectively. The reliability of the image analysis (the presence of PSCL) was assessed by a simple kappa coefficient. Kappa values were categorized as follows: > 0.8, very good; between 0.6 and 0.8, good; between 0.4 and 0.6, moderate; between 0.2 and 0.4, fair; and < 0.2, poor. The concordance between the two observers (interobserver reliability) was very good (k = 0.84). The intra-observer reliability was also very good (k = 0.92).

Statistical analyses. Data are reported as means ± standard deviations. All statistical analyses were performed using EZR software (Saitama Medical Center Jichi Medical University, Tochigi, Japan). Pearson correlation coefficients and linear/logistic regression analyses were used to assess correlations among the indicated values after normal distribution was confirmed using the Kolmogorov-Smirnov test. BME-V, the presence of PSCL, and SIFK grade were evaluated as dependent variables, whereas age, BMI, duration from injury to surgery, FTA, and MME were evaluated as independent variables. Linear regression analysis for BME-V as a dependent variable was performed excluding 10 knees with no BME to maintain normal distribution. A good correlation was defined as $R^2 \geq 0.50$, moderate correlation as $0.49 \geq R^2 \geq 0.30$, and weak correlation as $R^2 < 0.30$ [16]. One-way analysis of variance was used to compare values among the groups. Statistical significance was set at two-tailed $p < 0.05$.

Results

Patient demographics are shown in Table 1. The mean age was 59.2 years (range, 39-84 years). PSCL in the TKA, UKA, and pullout groups was present in 3 (43%), 1 (25%), and 12 (67%) cases, respectively. The SIFK grades (1/2/3/4) in the TKA and UKA groups were 0/1/3/3 and 2/0/1/1, respectively, whereas no SIFK was identified in the pullout group. Significantly larger BME-V (28.3 ± 20.5 cm^3) was observed in the TKA group than in the UKA group (2.3 ± 2.3, $p < 0.01$) and pullout group (4.1 ± 7.9 cm^3).

Pearson correlation analysis revealed that duration positively correlated with MME (coefficient: 0.51, $p < 0.01$), that MME was positively correlated with BME-V (coefficient: 0.70, $p < 0.01$) and that duration, MME, and BME-V were positively correlated with SIFK grade (coefficient: 0.61, $p < 0.01$; coefficient: 0.72, $p < 0.01$; coefficient: 0.56, $p < 0.01$) (Fig. 3). Multivariate linear regression analysis revealed that age, MME, and duration were significant factors for high-grade SIFK (β coefficient = 0.25, 0.31, and 0.55, respectively) and that MME was a significant factor for large BME-V (Table 2, n = 19, β coefficient = 0.66). Multivariate logistic regression analysis showed that duration was a significant factor for the presence of PSCL (odds ratio = 0.94, $p < 0.05$; Table 3). Age, BMI, and FTA were not cor-

Table 1 Demographic and clinical characteristics

	TKA group	UKA group	Pullout group	*P*-value
Number of patients	7	4	18	
Age (years)	74.0 ± 8.0[b]	69.0 ± 9.8	62.0 ± 7.7	< 0.01*
Height (m)	1.48 ± 0.1	1.49 ± 0.1	1.54 ± 0.1	
Weight (kg)	50.9 ± 7.8[b]	56.3 ± 11.9	63.2 ± 9.1	0.02*
BMI (kg/m^2)	23.1 ± 2.2	25.2 ± 4.4	26.3 ± 3.4	
Duration from injury to MRI (weeks)	44.8 ± 31.5[b]	35.7 ± 40.5[b]	6.0 ± 8.2	< 0.01*
Femorotibial angle (°)	180.6 ± 3.0	178.0 ± 0.8	177.6 ± 1.6	
Kellgren–Lawrence grade 0/1/2/3/4	0/0/0/3/4	0/0/1/3/0	2/10/6/0/0	
MME (mm)	7.3 ± 1.1[a,b]	4.5 ± 0.8	4.8 ± 1.0	< 0.01*

Data are presented as mean ± standard deviation.
TKA, total knee arthroplasty; UKA, uni-compartmental knee arthroplasty; BMI, body mass index; MRI, magnetic resonance imaging; MME, medial meniscus extrusion.
*Significant difference ($p < 0.05$) determined using one-way analysis of variance. [a]Significant difference compared to the UKA group. [b]Significant difference compared to the pullout group.

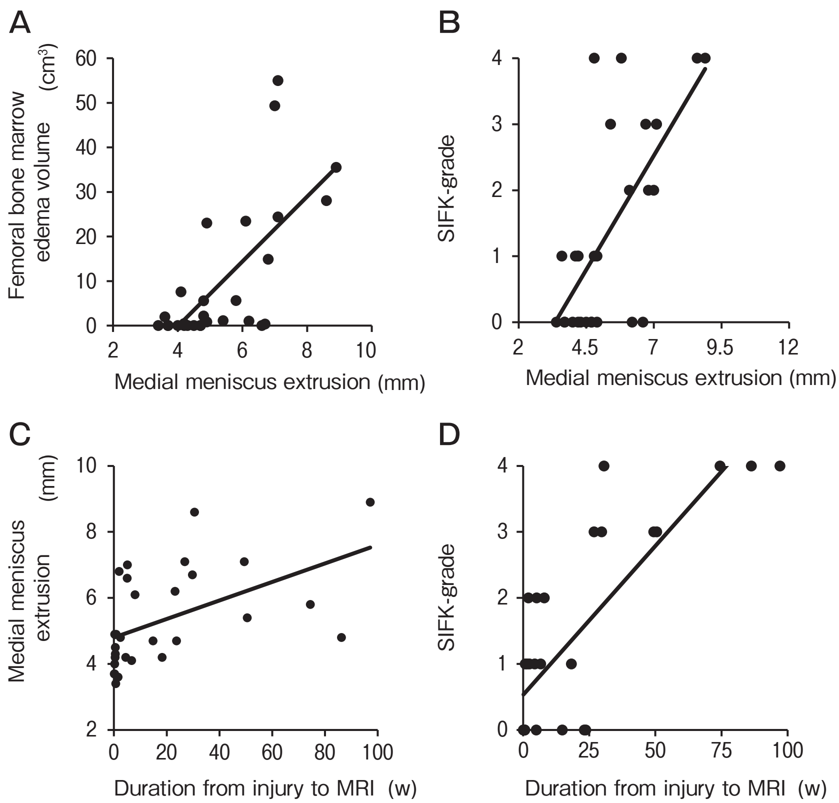

Fig. 3 Correlation among dependent variables and independent variables. (**A**) Correlation between MME and BME-V. (**B**) Correlation between MME and SIFK grade. (**C**) Correlation between duration from injury to MRI (diagnostic delay) and MME. (**D**) Correlation between diagnostic delay and SIFK grade.
BME-V, bone marrow edema volume; -SIFK, subchondral insufficient fracture of the knee; MME, medial meniscus extrusion; MRI, magnetic resonance imaging.

Table 2 Multivariate linear regression analysis

Dependent variables	Independent variables	B coefficient	β coefficient	Standard error	*P*-value	R^2	Analysis *P*-value
Femoral BME-V (cm^3) (n=19)	Age (year)	0.41	0.22	0.35	0.26	0.40	0.01
	MME (mm)	7.58	0.66	2.37	<0.01*		
	Duration (week)	−0.05	−0.10	0.12	0.70		
SIFK grade (n=29)	Age (year)	0.04	0.25	0.14	0.01*	0.78	<0.01
	MME (mm)	0.31	0.31	0.11	<0.01*		
	Duration (week)	0.03	0.55	0.006	<0.01*		

R^2, adjusted R-squared; BME-V, bone marrow edema volume; SIFK, subchondral insufficiency fracture of the knee; MME, medial meniscus extrusion.
*Significant difference was calculated using the forward stepwise method to evaluate risk factors for femoral BME-V and high-grade SIFK.

Table 3 Multivariate logistic regression analysis

Dependent variables	Independent variables	OR	*P*-value	95% CI
PSCL (n=29)	Age (year)	1.05	0.36	0.94–1.2
	BMI (kg/m^2)	1.09	0.60	0.79–1.5
	Duration (week)	0.94	<0.05*	0.89–1.0

PSCL, posterior shiny-corner lesion; CI, confidence interval; BMI, body mass index; OR, odds ratio.
*Significant difference was calculated using the forward stepwise method to evaluate risk factors for PSCL.

related with any dependent variables.

Discussion

The most important finding of this study is that MME is positively correlated with BME-V and that duration is positively correlated with SIFK grade and negatively correlated with PSCL in the MMPRT knee. Many clinical and biomechanical studies on MMPRT have been conducted [2, 4, 17], and good clinical outcomes have been reported after repair surgery, compared to those after conservative treatment [18, 19]. Nevertheless, few studies have reported that BME (including PSCL) and SIFK are associated with MMPRT, and the extent of BME or SIFK after MMPRT remained largely unknown.

BME associated with meniscus injury and knee OA has been reported using MRI in several studies [3, 4, 9, 20]. Meniscal pathologies including derangement, mechanical knee malalignment, and high compartmental loads have been reported as risk factors for BME [3, 4, 6]. Associations between BME and other factors have also been reported. There is a significant association between BME and chondral lesions for medial femoral condyle (MFC); however, BME was not associated with pain scores preoperatively or 1-year postoperatively in a previous study [20]. Furthermore, a large BME is associated with increased knee pain, while BME regression is associated with decreased knee pain [21].

Imaging characteristics of MMPRT and associations between MMPRT and BME, cartilage lesion, PSCL, or SIFK resulting in TKA have been reported [1, 2, 8, 10]. MM posterior root lesions are commonly detected in symptomatic patients [22], and determining the characteristic findings in these patients provides high diagnostic accuracy [12]. Arthroscopic findings of a previous study revealed that MFC lesions accompanying MMPRT were located more medially and progressed faster than those accompanying non-root horizontal tear [23]. Femoral condyle insufficiency fracture is frequently associated with overlying cartilage loss and ipsilateral meniscal injury. The extent of cartilage loss and meniscal damage, in addition to the reduced range of motion in the knee at the time of presentation, is significantly associated with progression to TKA [24]. MMPRT frequently causes high-grade SIFK after conservative treatment, especially in cases with severe MME (> 5 mm) [8].

A biomechanical approach in MR interpretation helps assess osseous contusion and ligament rupture and detects delicate (but significant) abnormalities [2]. We consider that a severe increase in MME leads to a severe increase in the contact pressure applied on the femoral condyle, which results in a large BME-V. Worsening of MME should be prevented because patients with decreased BME (not limited MMPRT) typically do not progress to high-grade SIFK [8]. It has been reported that MME and duration from injury to surgery were positively correlated, and that the SIFK grade had strong, positive correlations with duration and MME [25]. However, the occurrence of MME immediately after MMPRT varies among patients; a large BME occurred immediately after injury in some patients, thus resulting in no correlation between BME-V and duration. In the present study, BMI was not associated with dependent variables, consistent with previous findings [6, 8]. Duration had a negative correlation with PSCL. The PSCL might occur at the time of injury due to minor trauma and then gradually improve, and subchondral lesions often become free from loading after the initial tear [10]. These findings are consistent with previous findings suggesting that bone bruising is less severe and regresses within a short period after low-energy trauma, whereas healing of lesions caused by high-energy trauma, including those due to anterior cruciate ligament injury, may require years [26]. Duration was positively correlated with SIFK grade; high-grade SIFK (3, 4) required operative treatment such as TKA or UKA, whereas low-grade SIFK (1, 2) associated with BME could be improved within 5 months with conservative treatment, such as toe-touch gait. However, even low-grade SIFK can sometimes convert to high-grade SIFK when the lesion size is large [8]. Early diagnosis and MMPRT pullout repair can prevent severe MME and high-grade SIFK, which can in turn lead to arthroplasty.

This study is not without limitations. First, the sample size was small as men were categorically excluded for having different bone density than women. As a result, the findings of this study, which included only middle-aged women, cannot be generalized to other populations. Second, this is a cross-sectional and retrospective study, which cannot determine causal relationships among factors. Third, bone density or metabolic markers, which might be associated with

SIFK, were not examined in this study. Furthermore, MRI examinations were performed twice, but not for all patients. Only preoperative images were evaluated, and the course of BME change was not evaluated. Individual differences in the frequency of BME or PSCL were also not evaluated. Preoperative MRI examinations at two different time points per patient might be useful for obtaining more sensitive results.

In conclusion, a long duration of MMPRT can lead to severe MME and high-grade SIFK (3 and 4), resulting in knee arthroplasty. The occurrence of SIFK could be prevented by MMPRT pullout repair in the early phase before MME severely progresses. PSCL might be useful to determine whether patients are in the early phase, especially in cases with an unclear occurrence of a painful popping episode.

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