European Radiology (2019) 29:6372–6384
https://doi.org/10.1007/s00330-019-06220-w

MUSCULOSKELETAL

The International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine classification of knee meniscus tears: three-dimensional MRI and arthroscopy correlation

Avneesh Chhabra[1,2,3,4] · Oganes Ashikyan[1] · Rocco Hlis[1] · Anthony Cai[1] · Kyle Planchard[1] · Yin Xi[1] · Christopher McCrum[2] · Jay Shah[2]

Received: 15 November 2018 / Revised: 20 March 2019 / Accepted: 3 April 2019 / Published online: 21 May 2019

Abstract

Objectives To introduce MRI-based International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) classification system of meniscal tears and correlate it to the surgical findings from arthroscopy. We hypothesized that the ISAKOS classification will provide good inter-modality and inter-rater reliability for use in the routine clinical practice of radiologists and orthopedic surgeons.

Methods In this HIPAA-compliant cross-sectional study, there were 44 meniscus tears in 39 patients (26 males, 16 females). Consecutive arthroscopy-proven meniscal tears (March 2017 to December 2017) were evaluated by two board-certified musculoskeletal radiologists using isotropic three-dimensional (3D) MRI user-defined reconstructions. The surgically validated ISAKOS classification of meniscal tears was used to describe medial meniscus (MM) and lateral meniscus (LM) tears. Prevalence-adjusted bias-adjusted kappa (PABAK) and conventional kappa, and paired *t* test and intra-class correlation coefficient (ICC) were calculated for categorical and numerical variables, respectively.

Results For the MM, the PABAK for location, depth, length (ICC), pattern, quality of meniscus tissue, and zone was 0.7–1, 0.65, 0.57, 0.67, 0.78, and 0.39–0.7, respectively. For the LM, the PABAK for location, depth, length (ICC), pattern, quality of meniscus tissue, zone, and central to popliteus hiatus was 0.57–0.95, 0.57, 0.74, 0.93, 0.38, 0.52–0.67, and 0.48, respectively. The mean tear lengths were larger on MRI than on arthroscopy (mean difference MM 9.74 mm (6.66 mm, 12.81 mm; $p < 0.001$), mean difference LM 4.04 mm (0.31 mm, 7.76 mm; $p = 0.034$)).

Conclusions The ISAKOS classification of meniscal tears on 3D MRI provides mostly moderate agreement, which was similar to the agreement at arthroscopy.

Key Points

• *There is a fair to good inter-method correlation in most categories of ISAKOS meniscus tear classification.*
• *The tear lengths are significantly larger on MRI than on arthroscopy.*
• *The inter-reader correlation on 3D MRI is moderate to excellent, with the exception of lateral meniscus tear patterns.*

Keywords Knee injuries · Meniscus · Imaging, three-dimensional · Magnetic resonance imaging · Arthroscopy

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00330-019-06220-w) contains supplementary material, which is available to authorized users.

✉ Avneesh Chhabra
avneesh.chhabra@utsouthwestern.edu

[1] Radiology, UT Southwestern Medical Center, 5323 Harry Hines Blvd, Dallas, TX 75390-9178, USA

[2] Orthopedic Surgery, UT Southwestern Medical Center, 5323 Harry Hines Blvd, Dallas, TX 75390-9178, USA

[3] Musculoskeletal Radiology, UT Southwestern Medical Center, 5323 Harry Hines Blvd, Dallas, TX 75390-9178, USA

[4] Johns Hopkins University, Baltimore, USA

Abbreviations

2D	Two-dimensional
ISAKOS	The International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine
mm	Millimeters
MRI	Magnetic resonance imaging
PABAK	Prevalence-adjusted bias-adjusted kappa
SD	Standard deviation

Introduction

The knee menisci are C-shaped structures composed of collagen and fibrocartilage and serve many essential functions, such as shock absorption, axial load distribution, joint lubrication, and stability [1, 2]. The predominant circumferentially and longitudinally oriented type I collagen bundles provide the meniscus with hoop strength, and the thinner radial fibers tie the collagen bundles together forming a lattice that provides an essential structural support for the menisci [3, 4]. Meniscus tears can result in important clinical implications such as symptoms of pain, locking and joint instability, and, importantly, cartilage loss and development of osteoarthrosis [5–7]. The menisci may tear from degenerative or traumatic mechanisms, and eventually different patterns of meniscal tears can emerge [8]. The treatments of these lesions vary from conservative management to partial meniscectomy, meniscal repair, or transplantation [9–11]. In general, there is a lack of data regarding the relevance of different morphologic types of meniscal tears, proposed classifications, or their treatments with respect to the future implications of longitudinal development of osteoarthrosis [12, 13]. In addition, the terminology used for description of the meniscus tear and extent vary based on preference of the knee surgeon and interpreting radiologist.

The International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) Knee Committee formed a Meniscus Documentation Subcommittee in 2006 with an overarching goal of developing a reliable, international meniscal evaluation and documentation system to facilitate outcomes assessment [14]. The ISAKOS classification exhibited sufficient inter-observer reliability among the orthopedic surgeons for pooling of data from international clinical trials designed to evaluate the outcomes of treatment for meniscal tears.

From the non-invasive diagnostic perspective, magnetic resonance imaging (MRI) is the modality of choice for the evaluation of meniscus tears, and a definitive diagnosis of an intact or a torn meniscus can be made in 90–95% of knee MRI interpretations [15–20]. The tears are diagnosed based on morphologic alterations and/or hyperintense signal alterations that disrupt the meniscal articular surface on intermediate-weighted or T2-weighted sequences [17, 21, 22]. With wider availability of the newer and higher-field MR scanners, thin-slice (3–4 millimeters (mm)) imaging is routinely obtained for two-dimensional (2D) knee MRIs [23–25]. In recent years, 3D MR imaging with isotropic resolution is being increasingly used and has been shown to provide similar interpretation accuracy as 2D MR imaging for the meniscus tears [26–30]. This isotropic imaging allows sub 1-mm user-defined reconstructions in multiple arbitrary planes, especially along the axial planes of the medial or lateral menisci, with depictions of the tear in similar orientations as arthroscopy [31]. Thus, the extent and axial rim width of the meniscus can both be evaluated.

While many different meniscus tear patterns have been described in the literature [32–34] and are used in any given musculoskeletal-orthopedic practice, neither MRI nor arthroscopy guarantees complete detection of all knee pathologies. Furthermore, MRI results are not always consistent with arthroscopic findings [35].

Thus, there is a need for a similar MRI-based ISAKOS classification system of meniscus tears for consistent reporting. The aim of this study was to apply MRI-based ISAKOS classification system of meniscal tears on high-resolution isotropic 3D MR imaging with user-defined reconstructions and correlate it to surgical findings at the time of arthroscopy. We hypothesized that the ISAKOS classification provides good inter-modality and inter-rater reliability for use in the routine clinical practice of radiologists and orthopedic surgeons.

Methods

This was a cross-sectional retrospective analysis with institutional review board approval. The informed consent was waived.

Patient population

A consecutive series of patients were included who underwent arthroscopy of the knee for a variety of reasons, such as cruciate ligament injury, meniscus tear, and cartilage repair procedures from March 2017 to December 2017. The inclusion criteria were adults (16–100 years), both genders, arthroscopy-proven discrete meniscus tears, medial and lateral meniscus tears (both of which could be present in the same knee), 3D isotropic fat-suppressed intermediate-weighted fast spin echo imaging, and 3-Tesla (T) MR imaging. The exclusion criteria were metal or susceptibility artifacts, prior meniscus surgery, lack of 3D isotropic MR imaging or missing arthroscopy photographs, and findings in the electronic health

Table 1 Guide for magnetic resonance imaging evaluation of meniscus tear based on ISAKOS classification (modified original arthroscopy-based classification)

Criteria for meniscus tear identification	Signal hyperintensity breaching the articular surface of the meniscus and/or abnormal morphology
Tear types	
Horizontal tear	Runs parallel to the tibial plateau, involves either one of the articular surfaces or the central free edge, dividing the meniscus into superior and inferior portions
Longitudinal tear	Runs perpendicular to the tibial plateau and parallel to the long axis of the meniscus, dividing the meniscus into central and peripheral portions
Radial tear	Runs perpendicular to both the tibial plateau and the long axis of the meniscus and extends from the free edge towards the periphery along the radial plane of the meniscus (helpful signs—truncated triangle, cleft, ghost, marching cleft)
Bucket handle tear	Bucket handle tear is a longitudinal tear with central migration of the inner "handle" fragment
Horizontal flap tear	Horizontal flap tear has a displaced flap component of a predominantly horizontal tear
Complex tear	Complex tear encompasses 2 or more tear directions (patterns)
Categories	
Tear depth	Partial or complete, depending upon the tear extending through one or both surfaces of the meniscus
Rim width	zone 1—0 to 3 mm, zone 2—3 to 5 mm, zone 3—5 mm
Radial location	Indicate whether the tear is posterior, mid body, or anterior in location
Central to popliteus hiatus	Yes/no. A tear of the lateral meniscus that extends partially or completely in front of the popliteal hiatus should be graded as central to the popliteal hiatus
Tear pattern	Tears should be graded as per the predominant tear pattern, described above. Complex tears include 2 or more tear patterns
Quality of the tissue	Degenerative characteristics include multiple tear patterns, diffusely increased signal and globular enlargement, or irregular meniscal tissue with fibrillation/ fraying changes
Length of tear	The length of a tear in millimeters is the distance the tear extends into the meniscus

records. There were 44 3 Tesla studies with 3D imaging. Five studies were excluded based on the absence of meniscal pathology.

Data collection

A detailed electronic chart review was then performed by three medical students. Demographic data (age, gender), laterality of the knee and meniscus, and mean time of MRI to arthroscopy date (in days) were recorded for each patient. All information was charted on a Microsoft 2010 Excel spreadsheet. The arthroscopy images and findings were retrieved from the electronic health records and re-reviewed by the surgeon. All arthroscopies had been performed by the same orthopedic surgeon with sports fellowship training and 10 years of overall of orthopedic surgery experience. The arthroscopy had been recorded in a standardized manner depicting different compartments of the knee in a sequential manner displaying all surfaces of both medial and lateral menisci with arthroscopy probes in the field of view.

The arthroscopic data acquired during surgery was stored in the electronic health records of the patients. It was retrieved and reviewed retrospectively along with surgical reports.

The images of the patellofemoral compartment, lateral gutter, medial compartment, and lateral compartment were obtained in a standardized manner in the same sequence with at least three to four images of each compartment and with probes in the field of view. A second sports fellowship–trained orthopedic surgeon reviewed and measured tears on all images 4 months after the first surgeon's readings. A consensus training was done on four cases prior to the review of cases.

3D MRI protocol

The 3D imaging was obtained on 3-T scanners (Skyra, Siemens; and Achieva and Ingenia, Philips) using multichannel phased array knee coils from the same tertiary care institution. The sequence parameters of the intermediate-weighted fast spin echo sequence on both scanner platforms included repetition time = 1100 − 1200 ms, echo time = 37–42 ms, fat suppression = spectral adiabatic inversion recovery, field of view read = 180 mm, voxel = $0.65 \times 0.65 \times 0.65$ mm^3 acquired, plane = coronal acquisition, slab = 1, slice oversampling = 45.5%, phase oversampling = 0%, slices per slab = 176, averages = 1.4, acceleration factor = 3, turbo factor = 68, and imaging time = 7 min.

MR imaging data evaluation

The MR imaging evaluation was performed independently by two musculoskeletal fellowship–trained

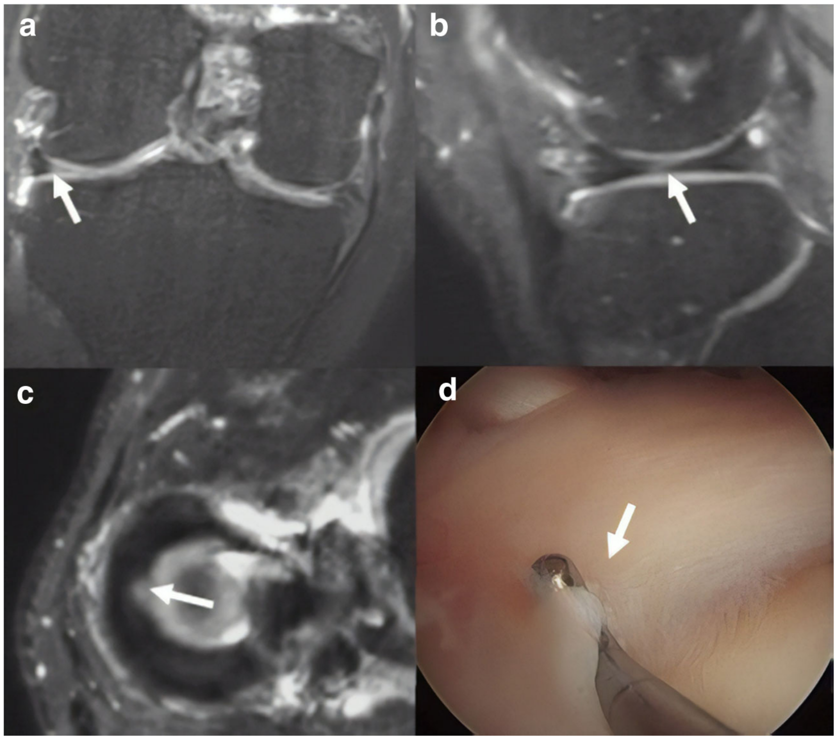

Fig. 1 A 56-year-old male with a radial tear of the lateral meniscus. Three-dimensional multiplanar reconstructions including user-defined coronal (**a**), sagittal (**b**), and axial (**c**) planes show a radial tear of the posterior horn of the lateral meniscus on non-contrast MRI. A complex tear of the medial meniscus is also seen. Reader 1 MRI ISAKOS classification: depth—complete; rim width—zones 2, 3; radial location—mid body; central to popliteus hiatus—no; tear pattern—radial; quality—non-degenerative; tear length—6 mm (millimeters). Reader 2 MRI ISAKOS classification: depth—partial; rim width—zone 3; radial location—mid body; central to popliteus hiatus—no; tear pattern—radial; quality—degenerative; tear length—4 mm (millimeters). Reader 1 arthroscopy (**d**) ISAKOS classification: depth—partial; rim width–zone 3; radial location—mid body; central to popliteus hiatus—no; tear pattern—radial; quality—degenerative; tear length—4 mm. Reader 2 arthroscopy ISAKOS classification: depth—partial; rim width—zones 2, 3; radial location—mid body; central to popliteus hiatus—no; tear pattern—radial; quality—degenerative; tear length—6 mm

Table 2 Demographics and meniscus tear type, length, and distribution on magnetic resonance imaging and arthroscopy

	Sex	Age (years)	Mean time from MRI[a] to arthroscopy (days)	Right knees (*n*)	Left knees (*n*)	MM[b] tears (*n*)	LM[c] tears (*n*)
Male	26	29.27 ± 11.79					
Female	13	36.69 ± 15.36					
Total	39	31.74 ± 13.36	88.46 ± 71.18	21	18	23	21
	Tears on arthroscopy (*n*)	Mean (mm[d])	Standard deviation	Tears on MRI (*n*)	Mean (mm)	SD[e] (mm)	
Radial	5	2.8	0.45	7	6.07	4.75	
Horizontal	1	28	12.86	1	24		
Longitudinal	9	14.89	6.57	5	24.2	6.5	
Bucket handle	9	39	5.52	11	50.27	7.85	
Horizontal flap	2	14	14.14	3	15.33	14.57	
Complex	18	23	7.65	17	32.29	10.38	

[a] Magnetic resonance imaging

[b] Medial Meniscus

[c] Lateral Meniscus

[d] Millimeters

[e] Standard Deviation

board-certified radiologists after a consensus reading on four different meniscus tears for training purposes, which was part of the final set of reads. The readers were blinded to each other's findings, and the readings were performed 2 weeks following the training date. An ISAKOS classification template guide [14] was available for recording the findings (Table 1). The medical students recorded the findings and prompted the radiologists to find and evaluate the tear of medial, lateral, or both menisci in the same knee as the study was not aimed at testing the accuracy or sensitivity of detection of meniscus tears. The readers were also blinded to the actual arthroscopy findings as well as to the surgically recorded type and extent of each meniscus tear. A tear with two or more directions was termed as a complex type, which also included the longitudinal flap tear variant that has been traditionally described as a separate subtype in the ISAKOS classification. The imaging evaluation was performed on PACS (picture archiving and communication system) with in-line processing of the 3D isotropic images in coronal, sagittal, and user-defined axial planes of both menisci [31]. Less than a minute was required to create such images in real time, and another several minutes to evaluate each meniscus. These axial planes allowed assessment of the length of the meniscus tear, rim width, and zonal location like arthroscopy (Fig. 1). No images were degraded by motion or precluded the reading assessment.

Arthroscopy data evaluation

Two fellowship-trained sports surgeons evaluated the arthroscopy images of each case. The reads were recorded using the ISAKOS classification system and blinded to the original MRI reading and re-review results of the 3D MRI by the radiologists. The meniscus tear length was estimated based on the probe diameter.

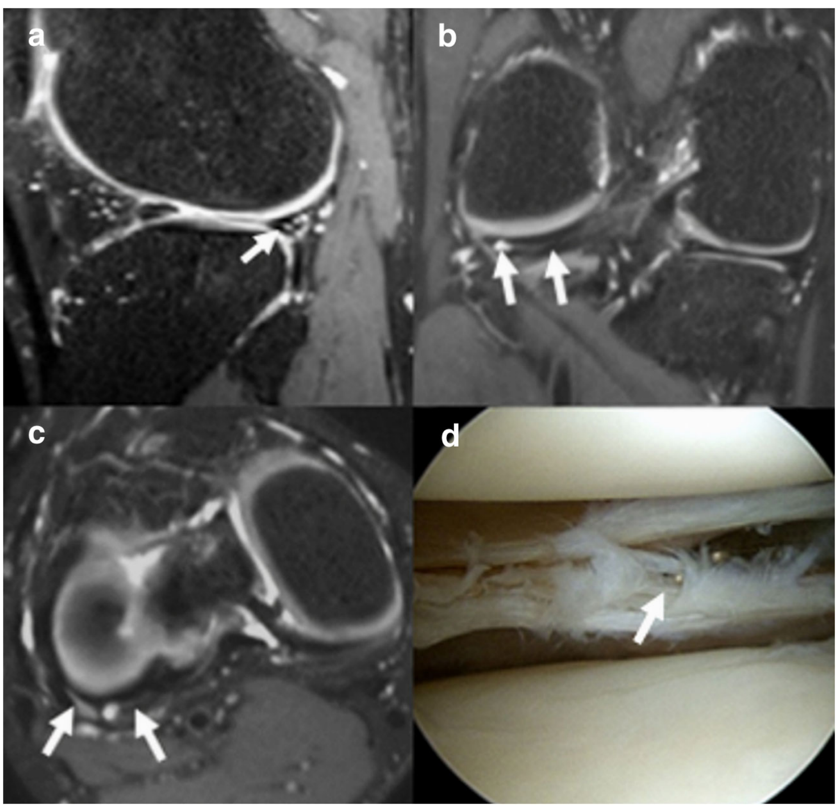

Fig. 2 A 26-year-old male with a horizontal tear. Three-dimensional multiplanar reconstructions including user-defined coronal (**a**), sagittal (**b**), and axial (**c**) planes show a horizontal tear of the posterior horn of the lateral meniscus with an intra- and para-meniscal cyst on non-contrast MRI. Reader 1 MRI ISAKOS classification: depth—complete; rim width—zones 1, 2, 3; radial location—posterior; central to popliteus hiatus—yes; tear pattern—horizontal; quality—degenerative; tear length—24 mm (millimeters). Reader 2 MRI ISAKOS classification: depth—complete; rim width—zones 1, 2, 3; radial location—posterior; central to popliteus hiatus—no; tear pattern—horizontal; quality—degenerative; tear length—28 mm (millimeters). Reader 1 arthroscopy (**d**) ISAKOS classification: depth—complete; rim width—zones 1, 2, 3; radial location—posterior; central to popliteus hiatus—no; tear pattern—horizontal; quality—degenerative; tear length—28 mm. Reader 2 arthroscopy ISAKOS classification: depth—complete; rim width—zones 1, 2, 3; radial location—posterior; central to popliteus hiatus—no; tear pattern—horizontal; quality—non-degenerative; tear length—25 mm

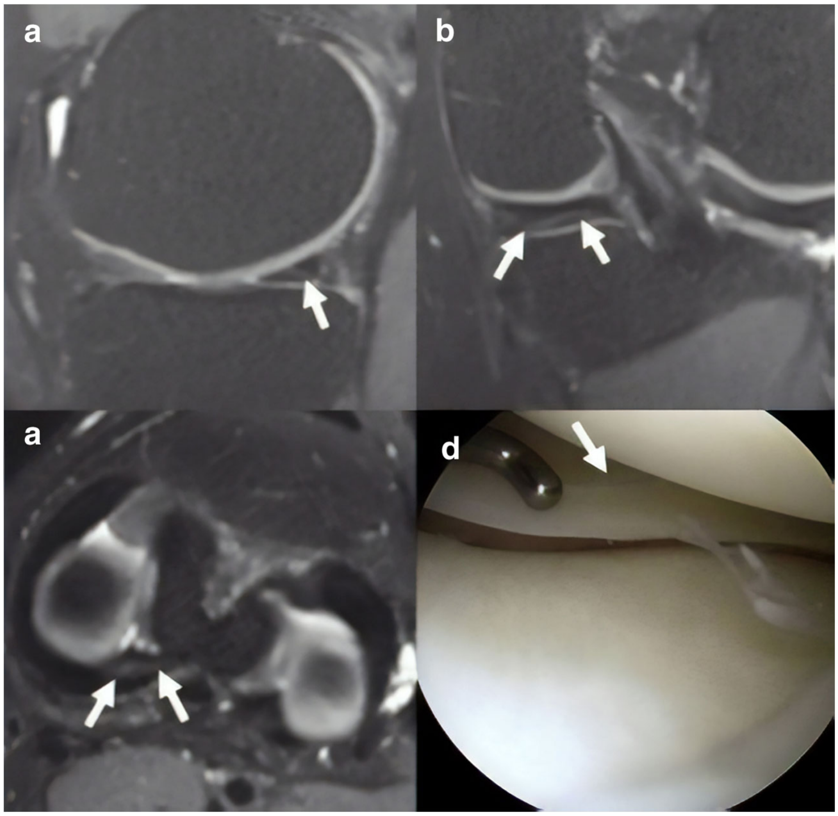

Fig. 3 A 24-year-old male with a longitudinal tear. Three-dimensional multiplanar reconstructions including user-defined coronal (**a**), sagittal (**b**), and axial (**c**) planes show a longitudinal tear of the posterior horn of the medial meniscus on non-contrast MRI. Reader 1 MRI ISAKOS classification: depth—complete; rim width—zone 2; radial location—posterior; quality—non-degenerative; tear pattern—longitudinal; tear length—17 mm (millimeters). Reader 2 MRI ISAKOS classification: depth—complete; rim width—zone 2; radial location—posterior; quality—non-degenerative; tear pattern—longitudinal; tear length—20 mm (millimeters). Arthroscopy reader 1 (**d**) ISAKOS classification: depth—complete; rim width—zone 2; radial location—posterior; tear pattern—longitudinal; quality—non-degenerative; tear length—16 mm. Arthroscopy reader 2 ISAKOS classification: depth—complete; rim width—zone 1; radial location—middle, posterior; tear pattern—longitudinal; quality—non-degenerative; tear length—25 mm

Statistical analysis

The data was recorded on a Microsoft Excel 2010 datasheet and tabulated as mean ± standard deviation (SD) and percentages. Prevalence-adjusted bias-adjusted kappa (PABAK) was calculated for categorical variables to account for imbalance of prevalence. Conventional kappa (*k*) was also calculated for categorical variables for comparison with previous studies. An intra-class correlation coefficient (ICC) was calculated for continuous variables. Ninety percent confidence intervals were also calculated. The Altman scale was used for categorization of PABAK and conventional kappa values; a value less than or equal to 0.20, 0.21–0.40, 0.41–0.60, 0.61–0.80, and 0.81–1.00 indicated poor, fair, moderate, good, and excellent agreements, respectively [36]. The Cicchetti scale was used for categorization of intra-class correlation (ICC); a value less than or equal to 0.40, 0.40–0.59, 0.60–0.74, and 0.75–1.00 indicated poor, fair, good, and excellent agreements, respectively [37]. Paired *t* tests were used to calculate the mean differences and associated 95% confidence interval between arthroscopy and MRI tear lengths. Bland-Altman plot data was calculated to display tear measurement agreement between readers. Normality of continuous data was checked by quantile-quantile plots for appropriateness on the normality assumption. Non-parametric sign-rank tests were also used to test differences in location. The significance level was set at 0.05. All analyses were done in SAS 9.4 (SAS Institute Inc.).

Results

Patient demographics and meniscal tear distribution

The patient demographics are summarized in Table 2.

There were 39 patients with ages of 31.7± 13.4 years (mean ± SD). There were 39 MRIs (21 right and 18 left knees) and 44

Table 4 Magnetic resonance imaging and arthroscopy correlations (conventional kappa)[d]

Variable	Surgeons	Radiologists	Surgeons vs. radiologists
LM[a] anterior	0.22 (− 0.32, 0.76)	0.7 (0.31, 1)	0.58 (0.17, 0.98)
LM middle	0.86 (0.59, 1)	0.77 (0.46, 1)	0.43 (0.01, 0.85)
LM posterior	1 (1, 1)	0.83 (0.51, 1)	0.91 (0.69, 1)
LM tear depth	0.67 (0.35, 1)	0.52 (0.16, 0.87)	0.54 (0.18, 0.9)
LM tear pattern	0.82 (0.63, 1)	0.82 (0.63, 1)	0.91 (0.78, 1)
LM tissue quality	0.42 (0.02, 0.81)	0.86 (0.59, 1)	0.33 (− 0.04, 0.7)
LM zone 1	0.71 (0.41, 1)	0.72 (0.43, 1)	0.53 (0.19, 0.87)
LM zone 2	0.8 (0.54, 1)	0.69 (0.37, 1)	0.64 (0.31, 0.97)
LM zone 3	0.89 (0.68, 1)	0.72 (0.43, 1)	0.61 (0.29, 0.93)
LM central to popliteus hiatus	0.9 (0.71, 1)	0.89 (0.69, 1)	0.49 (0.11, 0.87)
MM[b] anterior	0.33 (− 0.11, 0.77)	0.57 (0.22, 0.91)	0.56 (0.19, 0.94)
MM middle	0.65 (0.01, 1)	0.78 (0.36, 1)	0.72 (0.24, 1)
MM posterior[c]			
MM tear depth	0.78 (0.36, 1)	0.39 (− 0.09, 0.88)	0.29 (− 0.21, 0.79)
MM tear pattern	0.82 (0.62, 1)	0.74 (0.52, 0.96)	0.54 (0.31, 0.78)
MM tissue quality	1 (1, 1)	0.91 (0.75, 1)	0.78 (0.52, 1)
MM zone 1	0.25 (− 0.11, 0.6)	0.74 (0.41, 1)	0.39 (0.06, 0.71)
MM zone 2	0.59 (0.17, 1)	0.47 (− 0.13, 1)	0.38 (− 0.1, 0.87)
MM zone 3	0.74 (0.48, 1)	0.5 (0.21, 0.8)	0.61 (0.3, 0.91)

[a] Lateral meniscus (LM)

[b] Medial meniscus (MM)

[c] Agreement for the MM posterior is not available due to lack of variability

[d] Conventional kappa was used for categorical variables

meniscus tears. The mean time from MR imaging to arthroscopy was 88.46 ± 71.18 days.

Types and lengths of the meniscus tears

The most common meniscus tears were the complex type on both arthroscopy (18/44, 40.9%) and MR imaging (17/44, 38.6%). The least common types were the horizontal or horizontal flap tears with degenerative changes, which is expected in a surgically managed population. The bucket handle tears were the largest (39.0 ± 5.5 and 50.27 ± 7.9 mm), and the radial tears were the smallest (2.8 ± 0.2 and 6.0 ± 4.8 mm) on arthroscopy and MR imaging, respectively. Radial, horizontal, and longitudinal tears are shown in Figs. 1, 2, and 3, respectively.

Inter-rater correlation (surgeons)

The data is summarized in Tables 3 and 4. For the medial meniscus, the PABAK for location, depth, pattern, quality of meniscus tissue, and zone was good to excellent, good, excellent, excellent, and moderate to excellent, respectively. The conventional kappa for location, depth, pattern, quality of meniscus tissue, and zone was fair to good, good, excellent, excellent, and fair to good, respectively. The ICC for length was excellent. For the lateral meniscus, the PABAK for location, depth, pattern, quality of meniscus tissue, zone, and central to popliteus hiatus was excellent, moderate, excellent, excellent, good, and excellent, respectively. The conventional kappa for location, depth, pattern, quality of meniscus tissue, and zone was fair to excellent, good, excellent, moderate, good to excellent, and excellent, respectively. The ICC for length was excellent (Figs. 1, 2, and 3).

Inter-rater correlation (radiologists)

The data is summarized in Tables 3 and 4. For the medial meniscus, the PABAK for location, depth, pattern, quality of meniscus tissue, and zone was moderate to excellent, excellent, excellent, excellent, and fair to good, respectively. The conventional kappa for location, depth, pattern, quality of meniscus tissue, and zone was moderate to good, fair, good, excellent, and moderate to good, respectively. The ICC for length was good. For the lateral meniscus, the PABAK for location, depth, pattern, quality of meniscus tissue, zone, and central to popliteus hiatus was good to excellent, good,

Table 3 Magnetic resonance imaging and arthroscopy correlations (PABAK and ICC)[e]

Variable	Surgeons	Radiologists	Surgeons vs. radiologists
LM[a] anterior	0.81 (0.4, 1)	0.62 (0.19, 1)	0.76 (0.35, 1)
LM middle	0.81 (0.4, 1)	0.9 (0.51, 1)	0.57 (0.14, 1)
LM posterior	0.9 (0.51, 1)	1 (0.64, 1)	0.95 (0.57, 1)
LM tear depth	0.52 (0.09, 0.96)	0.71 (0.29, 1)	0.57 (0.14, 1)
LM tear length (ICC)	0.9 (0.77, 0.96)	0.87 (0.72, 0.95)	0.74 (0.45, 0.89)
LM tear length mean difference[b]	0.48 mm (− 2.66, 3.62; $p = 0.755$)	− 1.02 mm (− 4.97, 2.93; $p = 0.595$)	4.04 mm (0.31, 7.76; $p = 0.034$)[c]
LM tear pattern	0.85 (0.61, 1)	0.85 (0.61, 1)	0.93 (0.7, 1)
LM tissue quality	0.9 (0.51, 1)	0.43 (0, 0.86)	0.38 (− 0.05, 0.81)
LM zone 1	0.71 (0.29, 1)	0.71 (0.29, 1)	0.52 (0.1, 0.95)
LM zone 2	0.71 (0.29, 1)	0.81 (0.4, 1)	0.67 (0.25, 1)
LM zone 3	0.71 (0.29, 1)	0.9 (0.51, 1)	0.62 (0.19, 1)
LM central to popliteus hiatus	0.81 (0.4, 1)	0.9 (0.51, 1)	0.48 (0.04, 0.91)
MM[d] anterior	0.65 (0.25, 1)	0.57 (0.15, 0.98)	0.7 (0.3, 1)
MM middle	0.91 (0.55, 1)	0.91 (0.55, 1)	0.91 (0.55, 1)
MM posterior	1 (0.66, 1)	1 (0.66, 1)	1 (0.66, 1)
MM tear depth	0.65 (0.25, 1)	0.91 (0.55, 1)	0.65 (0.25, 1)
MM tear length (ICC)	0.94 (0.87, 0.97)	0.74 (0.49, 0.88)	0.57 (0.03, 0.85)
MM tear length mean difference[b]	2.57 mm (− 0.97, 6.10; $p = 0.147$)	− 0.57 mm (− 2.80, 1.67; $p = 0.606$)	9.74 mm (6.66, 12.81; $p < 0.001$)
MM tear pattern	0.82 (0.59, 1)	0.87 (0.64, 1)	0.67 (0.44, 0.9)
MM tissue quality	0.91 (0.55, 1)	1 (0.66, 1)	0.78 (0.39, 1)
MM zone 1	0.83 (0.44, 1)	0.22 (− 0.19, 0.62)	0.39 (− 0.01, 0.79)
MM zone 2	0.83 (0.44, 1)	0.74 (0.34, 1)	0.7 (0.29, 1)
MM zone 3	0.48 (0.06, 0.89)	0.74 (0.34, 1)	0.61 (0.2, 1)

[a] Lateral meniscus (LM)

[b] A paired *t* test was used to calculate mean difference and the associated 95% confidence interval

[c] The difference between surgeons and radiologists was calculated as MRI length − arthroscopy length

[d] Medial meniscus (MM)

[e] Prevalence-adjusted bias-adjusted kappa (PABAK) was calculated for categorical variables while an intra-class correlation coefficient (ICC) was calculated for continuous. PABAK is given unless otherwise indicated within parentheses in the first column

excellent, moderate, good to excellent, and excellent, respectively. The conventional kappa for location, depth, pattern, quality of meniscus tissue, and zone was good to excellent, moderate, excellent, excellent, good, and excellent, respectively. The ICC for length was excellent.

Inter-method (surgeons vs. radiologists) correlation

The data is summarized in Tables 3 and 4. For the medial meniscus, the PABAK for location, depth, pattern, quality of meniscus tissue, and zone was good to excellent, good, good, good, fair to good, respectively. The conventional kappa for location, depth, pattern, quality of meniscus tissue, and zone was moderate to good, fair, moderate, good, and fair to good, respectively. The ICC for length was fair. For the lateral meniscus, the PABAK for location, depth, pattern, quality of meniscus tissue, zone, and central to popliteus hiatus was moderate to excellent, moderate, excellent, fair, moderate to good, and moderate, respectively. The conventional kappa for location, depth, pattern, quality of meniscus tissue, and zone was moderate to excellent, moderate, excellent, fair, moderate to good, and moderate, respectively. The ICC for length was good.

Measurement differences between readers

The mean tear lengths were not significantly different between the two arthroscopy readers (mean difference MM 2.57 mm (− 0.97 mm, 6.10 mm; $p = 0.147$), mean difference LM 0.48 mm (− 2.66 mm, 3.62 mm; $p = 0.755$)). The mean tear lengths were not significantly different between the two MRI readers (mean difference MM − 0.57 mm (− 2.80 mm, 1.67 mm; $p = 0.606$), mean difference LM − 1.02 mm (− 4.97 mm, 2.93 mm; $p = 0.595$)). The mean tear lengths were significantly larger on MRI for the MM and LM (mean difference MM 9.74 mm (6.66 mm, 12.81 mm; $p < 0.001$), mean difference LM 4.04 mm (0.31 mm, 7.76 mm; $p = 0.034$)). Examples of this are shown in Figs. 4 and 5. The agreement between readers is given by Bland-Altman results in Table 5.

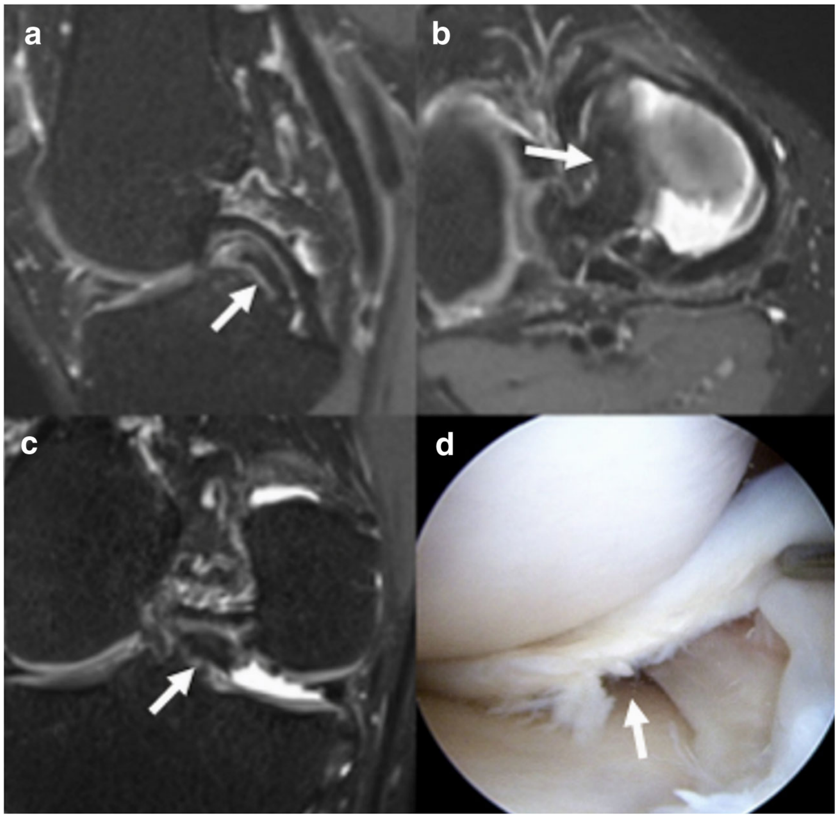

Fig. 4 A 35-year-old male with a bucket handle tear. 3-Dimensional multiplanar reconstructions including user-defined coronal (**a**), sagittal (**b**), and axial (**c**) planes show a bucket handle tear of the anterior horn, mid body, and posterior horn of the medial meniscus on non-contrast MRI. Reader 1 MRI ISAKOS classification: depth—complete; rim width—zones 2, 3; radial location—anterior, mid body, posterior; tear pattern—bucket handle; quality—non-degenerative; tear length—52 mm (millimeters). Reader 2 MRI ISAKOS classification: depth—complete; rim width—zones 2, 3; radial location—anterior, mid body, posterior; tear pattern—bucket handle; quality—degenerative; tear length—60 mm (millimeters). Arthroscopy reader 1 (**d**) ISAKOS classification: depth—complete; rim width—zones 2, 3; radial location—anterior, mid body, posterior; tear pattern—bucket handle; quality—degenerative; tear length—36 mm. Arthroscopy reader 2 (**d**) ISAKOS classification: depth—complete; rim width—zone 2; radial location—anterior, mid body, posterior; tear pattern—bucket handle; quality—degenerative; tear length—45 mm

Discussion

This study suggests that an MRI-based ISAKOS classification system may be employed in a multidisciplinary practice with different specialties using the same language for improved collaboration and better patient management. This surgically validated system can be used routinely in structured MRI reports and can aid in the longitudinal tracking of meniscus tears and their effect on the health of knee cartilage.

There was a fair to good inter-method correlation in most categories, and an excellent correlation in fewer categories when 3D MRI interpretations were compared with the surgical interpretations using PABAK. Conventional kappa values were slightly less than PABAK values due to underestimation by kappa as a result of imbalanced prevalence. Employment of a uniform and reproducible classification system across disciplines offers great potential for improved inter-disciplinary communications, better patient management planning, and longitudinal evaluation of meniscus tears and patient outcomes.

Tear depth

The tear depth inter-method correlation ranged from fair to moderate; prior studies have showed moderate correlation ($k = 0.29$–0.54 vs. $k = 0.46$–0.52, respectively) [14, 38].

Rim width

The rim width inter-method correlation was fair to good; correlation was fair in prior arthroscopy studies ($k = 0.38$–0.64 vs. $k = 0.25$–0.30, respectively) [14, 38]. In the original ISAKOS classification, if tears involved more than one zone, they were graded based on how far the tear extended into the meniscus [14]. For example, a complete radial tear that extends through zones 3, 2, and 1 was graded as a zone 1 tear. To be more

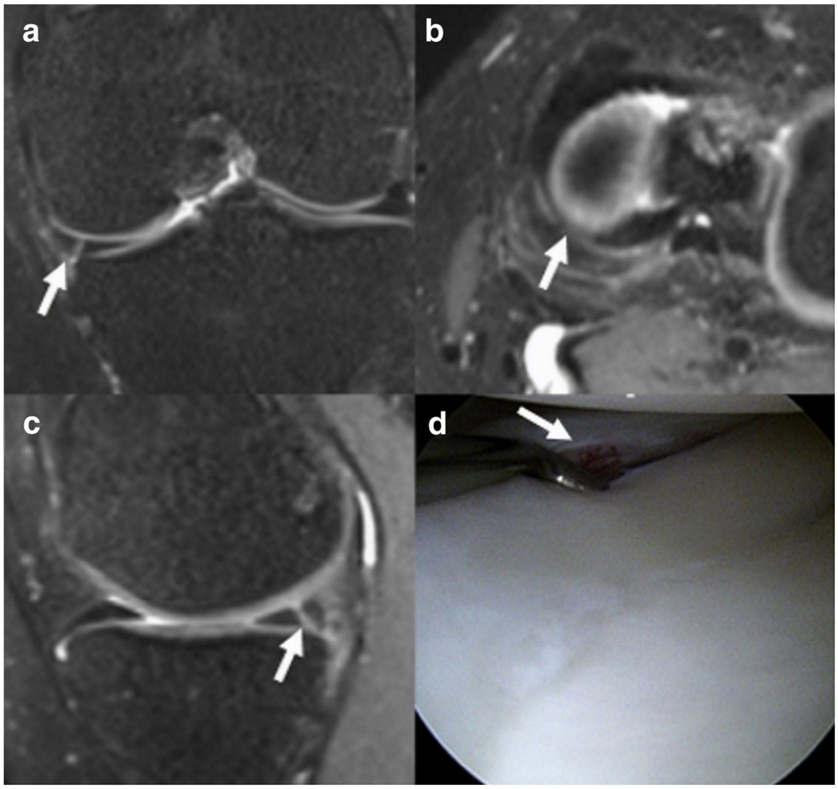

Fig. 5 A 17-year-old male with a longitudinal tear. Three-dimensional multiplanar reconstructions including user-defined coronal (**a**), sagittal (**b**), and axial (**c**) planes show a longitudinal tear of the mid body and posterior horn of the medial meniscus on non-contrast MRI. Reader 1 MRI ISAKOS classification: depth—complete; rim width—zones 1, 2, 3; radial location—mid body, posterior; tear pattern—longitudinal; quality—non-degenerative; tear length—30 mm (millimeters). Reader 2 MRI ISAKOS classification: depth—complete; rim width—zone 2; radial location—mid body, posterior; tear pattern—longitudinal; quality—non-degenerative; tear length—25 mm (millimeters). Arthroscopy reader 1 (**d**) ISAKOS classification: depth—complete; rim width—zone 2; radial location—mid body, posterior; tear pattern—longitudinal; quality—non-degenerative; tear length—12 mm. Arthroscopy reader 2 ISAKOS classification: depth—complete; rim width—zone 2; radial location—mid body, posterior; tear pattern—longitudinal; quality—non-degenerative; tear length—16 mm

detailed and precise, radiologists and surgeons chose to record all possible involved zones. Thus, user-defined axial reconstruction [31] from 3D MRI facilitated better determination of the zonal involvement. Better correlations in our study were likely attributable to the improved arthroscopy portals and current visualization techniques, surgical expertise, and high-resolution isotropic 3D spin echo imaging.

Radial location

Radial location inter-method correlation ranged from moderate to excellent; in prior studies, correlation ranged from moderate to good ($k = 0.43–0.91$ vs. $k = 0.46–0.61$, respectively).

Central to the popliteus hiatus

Moderate inter-method correlation was seen with respect to the categorization of the lateral meniscus tears as being central (in front) to the popliteal hiatus; correlation was fair to moderate in prior studies ($k = 0.49$ vs. $k = 0.36–0.42$, respectively) [14, 38]. Location in relation to the popliteus hiatus is clinically important as tears in front of the hiatus may not be repaired and are only debrided.

Tear pattern

There was moderate to excellent inter-method agreement for the pattern of meniscus tear type; there was good correlation in prior studies ($k = 0.54–0.91$ vs. $k = 0.63–0.72$, respectively) [14, 38]. It is important to note that the arthroscopic visualization of a complete pattern can be difficult at times; e.g., if the predominant direction of the tear towards the notch is longitudinal, and the displaced meniscus tissue blocks the field of view, the horizontal component towards the peripheral capsular attachment may be missed. It is only noticed if the meniscus is probed diligently after debridement. On the contrary, the MRI reader can easily appreciate multiple directions of the tear, including the perimeniscal cyst related to the peripheral horizontal component of the meniscus tear.

Table 5 Bland-Altman plot data

Variable	Reader 1	Reader 2	Mean	95% CI[a] of mean		p value	Limit of agreement	
LM[b] tear length	Radiologist 1	Radiologist 2	1	−3	5	0.595	−16	18
LM tear length	Radiologist 1	Surgeon 1	−3	−10	3	0.318	−32	26
LM tear length	Radiologist 1	Surgeon 2	−4	−9	2	0.178	−28	20
LM tear length	Radiologist 2	Radiologist 1	−1	−5	3	0.595	−18	16
LM tear length	Radiologist 2	Surgeon 1	−4	−9	1	0.077	−25	16
LM tear length	Radiologist 2	Surgeon 2	−5	−9	−1	0.020	−22	12
LM tear length	Surgeon 1	Radiologist 1	3	−3	10	0.318	−26	32
LM tear length	Surgeon 1	Radiologist 2	4	−1	9	0.077	−16	25
LM tear length	Surgeon 1	Surgeon 2	0	−4	3	0.755	−14	13
LM tear length	Surgeon 2	Radiologist 1	4	−2	9	0.178	−20	28
LM tear length	Surgeon 2	Radiologist 2	5	1	9	0.020	−12	22
LM tear length	Surgeon 2	Surgeon 1	0	−3	4	0.755	−13	14
MM[c] tear length	Radiologist 1	Radiologist 2	1	−2	3	0.606	−10	11
MM tear length	Radiologist 1	Surgeon 1	−8	−13	−3	0.002	−29	13
MM tear length	Radiologist 1	Surgeon 2	−11	−15	−6	< 0.0001	−31	10
MM tear length	Radiologist 2	Radiologist 1	−1	−3	2	0.606	−11	10
MM tear length	Radiologist 2	Surgeon 1	−9	−13	−5	< 0.0001	−28	10
MM tear length	Radiologist 2	Surgeon 2	−11	−16	−7	< 0.0001	−31	8
MM tear length	Surgeon 1	Radiologist 1	8	3	13	0.002	−13	29
MM tear length	Surgeon 1	Radiologist 2	9	5	13	< 0.0001	−10	28
MM tear length	Surgeon 1	Surgeon 2	−3	−6	1	0.147	−19	13
MM tear length	Surgeon 2	Radiologist 1	11	6	15	< 0.0001	−10	31
MM tear length	Surgeon 2	Radiologist 2	11	7	16	< 0.0001	−8	31
MM tear length	Surgeon 2	Surgeon 1	3	−1	6	0.147	−13	19

[a] Confidence interval (CI)

[b] Lateral meniscus (LM)

[c] Medial meniscus (MM)

Quality of the meniscal tissue

The meniscal tissue quality evaluation inter-method correlation was fair to good; in prior studies, correlation was moderate ($k = 0.33$–0.78 vs. $k = 0.47$, respectively). Small areas of myxoid signal were ignored during MRI interpretations as these are unlikely to be picked up by the surgeon on arthroscopy. Since arthroscopy picks up subtle areas of meniscus free edge fibrillations, which can be missed on MRI, it seems to be the best achievable correlation.

Lengths of tears

The length of tear inter-method correlation was moderate to good; in prior studies, correlation was good to excellent (ICC = 0.57–0.74 vs. ICC = 0.78–0.83, respectively). Meniscus tears were larger on MRI as compared with arthroscopy, especially the medial meniscus tears. This may be explained by several factors, such as MRI allows assessment of intra-substance extension of the lesion which may not be probable or could be missed on meniscus probing. In addition, the lesions may have partially healed or filled with granulation/fibrous tissue. Finally, the arthroscopy findings were estimated from the probe diameter and may not be completely accurate.

Inter-reader correlation was fair to excellent in most categories, with the exception of zone and radial location. Drops in correlation may be explained by underlying variations in the root attachment morphologies of the meniscus or other observer factors. Challenges with the diagnosis of lateral meniscus tears have also been discussed in prior reports [39].

Certain limitations need to be mentioned, such as the timing of arthroscopy could not be uniformly controlled due to the retrospective cross-sectional nature of the study. It is conceivable that the tears may have partially healed [39] or progressed in the interim. The sample size was small; however, this was an intentional to ensure that the uniform 3D isotropic imaging scan evaluations were compared with the arthroscopy findings. Furthermore, the small sample size may account for the observed large confidence intervals. Due to retrospective evaluation of arthroscopies, the surgeons did not have the advantage of tactile sensation provided by probing to evaluate the meniscal tears and quality of the tissue. In the future, a prospective study can be performed with real-time, head-to-head comparison of the 3D MRI and arthroscopy findings.

In conclusion, the ISAKOS classification of meniscal tears on 3D MRI provides mostly moderate agreement, which was similar to the agreement at arthroscopy. Our results may provide a basis for the use of ISAKOS classification for MRI in clinical practice.

Funding The authors state that this work has not received any funding.

Compliance with ethical standards

Guarantor The scientific guarantor of this publication is Avneesh Chhabra.

Conflict of interest Avneesh Chhabra declares relationships with the following companies: consultant for ICON Medical and Treace 3D Medical Inc. and receives royalties from Jaypee and Wolters. All other authors have no relationships to declare.

The authors of this manuscript declare no relationships with any companies, whose products or services may be related to the subject matter of the article.

Statistics and biometry Yin Xi, PhD (University of Texas Southwestern), is an author and provided statistical expertise.

Informed consent Written informed consent was waived by the Institutional Review Board.

Ethical approval Institutional Review Board approval was obtained.

Methodology
• retrospective
• cross-sectional study
• performed at one institution

References

1. Ahmed AM, Burke DL (1983) In-vitro measurement of static pressure distribution in synovial joints–part I: tibial surface of the knee. J Biomech Eng 105:216–225
2. Fukubayashi T, Kurosawa H (1980) The contact area and pressure distribution pattern of the knee. A study of normal and osteoarthrotic knee joints. Acta Orthop Scand 51:871–879
3. Petersen W, Tillmann B (1998) Collagenous fibril texture of the human knee joint menisci. Anat Embryol (Berl) 197:317–324
4. Renström P, Johnson RJ (1990) Anatomy and biomechanics of the menisci. Clin Sports Med 9:523–538
5. Burr DB, Radin EL (1982) Meniscal function and the importance of meniscal regeneration in preventing late medical compartment osteoarthrosis. Clin Orthop Relat Res:121–126
6. Fairbank TJ (1948) Knee joint changes after meniscectomy. J Bone Joint Surg Br 30b:664–670
7. Krause WR, Pope MH, Johnson RJ, Wilder DG (1976) Mechanical changes in the knee after meniscectomy. J Bone Joint Surg Am 58:599–604
8. Nguyen JC, De Smet AA, Graf BK, Rosas HG (2014) MR imaging-based diagnosis and classification of meniscal tears. Radiographics 34:981–999
9. Boyd KT, Myers PT (2003) Meniscus preservation; rationale, repair techniques and results. Knee 10:1–11
10. DeHaven KE (1985) Meniscus repair in the athlete. Clin Orthop Relat Res:31–35
11. McGinity JB, Geuss LF, Marvin RA (1977) Partial or total meniscectomy: a comparative analysis. J Bone Joint Surg Am 59:763–766
12. Bin SI, Jeong TW, Kim SJ, Lee DH (2016) A new arthroscopic classification of degenerative medial meniscus root tear that correlates with meniscus extrusion on magnetic resonance imaging. Knee 23:246–250
13. Jarraya M, Hayashi D, Roemer FW, Guermazi A (2016) MR imaging-based semi-quantitative methods for knee osteoarthritis. Magn Reson Med Sci 15:153–164
14. Anderson AF, Irrgang JJ, Dunn W et al (2011) Interobserver reliability of the International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) classification of meniscal tears. Am J Sports Med 39:926–932
15. Blankenbaker DG, De Smet AA, Smith JD (2002) Usefulness of two indirect MR imaging signs to diagnose lateral meniscal tears. AJR Am J Roentgenol 178:579–582
16. Crues JV 3rd, Mink J, Levy TL, Lotysch M, Stoller DW (1987) Meniscal tears of the knee: accuracy of MR imaging. Radiology 164:445–448
17. De Smet AA, Norris MA, Yandow DR, Quintana FA, Graf BK, Keene JS (1993) MR diagnosis of meniscal tears of the knee: importance of high signal in the meniscus that extends to the surface. AJR Am J Roentgenol 161:101–107
18. Lee SY, Jee WH, Kim JM (2008) Radial tear of the medial meniscal root: reliability and accuracy of MRI for diagnosis. AJR Am J Roentgenol 191:81–85
19. Oei EH, Nikken JJ, Verstijnen AC, Ginai AZ, Myriam Hunink MG (2003) MR imaging of the menisci and cruciate ligaments: a systematic review. Radiology 226:837–848
20. Subhas N, Sakamoto FA, Mariscalco MW, Polster JM, Obuchowski NA, Jones MH (2012) Accuracy of MRI in the diagnosis of meniscal tears in older patients. AJR Am J Roentgenol 198:W575–W580
21. Manaster BJ (1990) Magnetic resonance imaging of the knee. Semin Ultrasound CT MR 11:307–326
22. Stoller DW, Martin C, Crues JV 3rd, Kaplan L, Mink JH (1987) Meniscal tears: pathologic correlation with MR imaging. Radiology 163:731–735
23. De Smet AA, Blankenbaker DG, Kijowski R, Graf BK, Shinki K (2009) MR diagnosis of posterior root tears of the lateral meniscus using arthroscopy as the reference standard. AJR Am J Roentgenol 192:480–486
24. Koenig JH, Ranawat AS, Umans HR, Difelice GS (2009) Meniscal root tears: diagnosis and treatment. Arthroscopy 25:1025–1032
25. Tarhan NC, Chung CB, Mohana-Borges AV, Hughes T, Resnick D (2004) Meniscal tears: role of axial MRI alone and in combination with other imaging planes. AJR Am J Roentgenol 183:9–15
26. Gold GE, Busse RF, Beehler C et al (2007) Isotropic MRI of the knee with 3D fast spin-echo extended echo-train acquisition (XETA): initial experience. AJR Am J Roentgenol 188:1287–1293
27. Jung JY, Yoon YC, Kwon JW, Ahn JH, Choe BK (2009) Diagnosis of internal derangement of the knee at 3.0-T MR imaging: 3D isotropic intermediate-weighted versus 2D sequences. Radiology 253:780–787

28. Kijowski R, Davis KW, Blankenbaker DG, Woods MA, Del Rio AM, De Smet AA (2012) Evaluation of the menisci of the knee joint using three-dimensional isotropic resolution fast spin-echo imaging: diagnostic performance in 250 patients with surgical correlation. Skeletal Radiol 41:169–178
29. Kijowski R, Davis KW, Woods MA et al (2009) Knee joint: comprehensive assessment with 3D isotropic resolution fast spin-echo MR imaging–diagnostic performance compared with that of conventional MR imaging at 3.0 T. Radiology 252:486–495
30. Ristow O, Steinbach L, Sabo G et al (2009) Isotropic 3D fast spin-echo imaging versus standard 2D imaging at 3.0 T of the knee–image quality and diagnostic performance. Eur Radiol 19:1263–1272
31. Lim D, Lee YH, Kim S, Song HT, Suh JS (2013) Fat-suppressed volume isotropic turbo spin echo acquisition (VISTA) MR imaging in evaluating radial and root tears of the meniscus: focusing on reader-defined axial reconstruction. Eur J Radiol 82:2296–2302
32. Jee WH, McCauley TR, Kim JM et al (2003) Meniscal tear configurations: categorization with MR imaging. AJR Am J Roentgenol 180:93–97
33. Lee YG, Shim JC, Choi YS, Kim JG, Lee GJ, Kim HK (2008) Magnetic resonance imaging findings of surgically proven medial meniscus root tear: tear configuration and associated knee abnormalities. J Comput Assist Tomogr 32:452–457
34. Metcalf MH, Barrett GR (2004) Prospective evaluation of 1485 meniscal tear patterns in patients with stable knees. Am J Sports Med 32:675–680
35. Van Dyck P, Gielen J, D'Anvers J et al (2007) MR diagnosis of meniscal tears of the knee: analysis of error patterns. Arch Orthop Trauma Surg 127:849–854
36. Seigel DG, Podgor MJ, Remaley NA (1992) Acceptable values of kappa for comparison of two groups. Am J Epidemiol 135:571–578
37. Cicchetti D (1994) Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instrument in psychology. Psychol Assess 6:284–290
38. Dunn WR, Wolf BR, Amendola A et al (2004) Multirater agreement of arthroscopic meniscal lesions. Am J Sports Med 32:1937–1940
39. Weiss CB, Lundberg M, Hamberg P, DeHaven KE, Gillquist J (1989) Non-operative treatment of meniscal tears. J Bone Joint Surg Am 71:811–822