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Introduction of an MR-based semi-quantitative score for assessing partial meniscectomy and relation to knee joint degenerative disease: data from the Osteoarthritis Initiative

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Introduction of an MR-based Semi-quantitative Score for Assessing Partial Meniscectomy and Relation to Knee Joint Degenerative Disease: Data from the Osteoarthritis Initiative

Abstract

Objectives: To develop an MR-based semi-quantitative meniscus scoring technique for postoperative assessment of the degree of meniscal resection, to test its reproducibility and to study the relationship between amount of resection and degenerative disease burden.

Methods: We studied the right knee of 135 participants from the Osteoarthritis Initiative that underwent meniscal surgery an average of 14 years previously. The amount of meniscal resection was assessed on baseline 3.0T MRIs and calculated as meniscus resection score (MenRS) with a range of 0 to 18. Knee abnormalities at baseline and 48-month were graded using a modified Whole-Organ Magnetic Resonance Imaging Score (WORMS). Subjects were also stratified according to meniscal resection performed after injury versus without preceding injury. Statistical analysis included intra-class correlation coefficient (ICC) to determine reproducibility as well as regression models and partial correlations to correlate MenRS with WORMS outcomes.

Results: ICC values for intra- and inter-observer reproducibility of MenRS were 0.980 and 0.977, respectively. Overall, the amount of meniscal resection showed a significant correlation with baseline WORMS grades: higher MenRS was associated with higher total WORMS grades ($p=0.004$), cartilage ($p=0.004$), and ligament ($p<0.001$) subscores. However, no significant association between MenRS and change in WORMS grades over 48 months was found. The

relationship between MenRS and baseline WORMS grades did not change after adjusting for a reported history of knee injury.

Conclusions: Postoperative assessment of knee following partial meniscectomy using the newly developed MenRS showed excellent reproducibility and significant cross-sectional correlation with WORMS gradings.

Keywords

Partial meniscectomy; Meniscus; Magnetic resonance imaging; Knee osteoarthritis

Key Points

1. The newly developed semi-quantitative MR-based meniscal resection score demonstrated excellent reproducibility.
2. A significant correlation between the amount of meniscal resection measured using the newly developed score and the degree of overall knee joint degenerative disease and cartilage defects was found.

Abbreviations

BMI = body mass index
DESS = dual echo at steady state
ICC = intra-class correlation coefficient
KL = Kellgren-Lawrence
MenRS = Meniscus Resection Score
OA = Osteoarthritis
OAI = Osteoarthritis Initiative
WORMS = Whole-Organ Magnetic Resonance Imaging Score
WOMAC=Western Ontario and McMaster Universities Osteoarthritis Index

Introduction

Conservative treatment for meniscal tears [1]-[2], has been advocated over meniscectomy to reduce the risk of knee osteoarthritis (OA) [3-5]. However, partial meniscectomy is to some extent unavoidable [6] and is still commonly performed in the Western World with an incidence of 300 per 100,000 people annually [7].

A large number of predictive factors for the development of knee OA after meniscectomy have been discussed, with the amount of meniscus removed remaining the strongest predictor [8] and other important factors being degenerative tear [3], lateral meniscectomy [9] and age at surgery [10]. When comparing different meniscectomy techniques, partial meniscectomy has shown significantly better radiologic and functional outcomes than subtotal and total meniscectomy [11-13]; the benefits of more conservative meniscectomies were also highlighted by biomechanical evidence that joint stress on articular cartilage increased proportionally to the amount of meniscus resected [14-16]. Furthermore, Englund et al noted that the type of meniscal tears (degenerative or traumatic tears) may have confounded the association of the degree of resection with radiographic and symptomatic osteoarthritis [17; 18].

To the best of our knowledge, few studies have documented the amount of meniscal resection in clinical practice, thus the exact effect of various size of resection on subsequent OA risk remains unknown. Hede et al calculated the percentage of removed meniscal surface on postoperative drawings which were made to indicate the area excised from each meniscus, and found it to be inversely related to knee joint function [12]. A quantitative MRI method has been validated to determine the reduction in meniscal volume after meniscectomy [19; 20]; however, manual segmentation of the meniscus is a time-consuming process, limiting its potential to be used in large clinical studies [21].

To date, MR imaging is the standard technique to analyze the postoperative appearance of the resected meniscus [22], detect meniscal deficiencies [23; 24] and reveal OA-associated abnormalities [25; 26]. Thus, the purpose of our study was (1) to develop an MR-based semi-quantitative scoring approach to assess the degree of meniscal resection (meniscus resection score, MenRS), (2) to evaluate its reproducibility, (3) to correlate the MenRS with the degenerative disease burden both cross-sectionally and longitudinally.

Methods

This study utilized data from the Osteoarthritis Initiative (OAI; https://oai.epi-ucsf.org/), a longitudinal multi-center study of 4796 subjects aimed at identifying risk factors for knee OA. Informed consent was obtained from all participants; the study was compliant with the Health Insurance Portability and Accountability Act and was approved by the local institutional review boards of all participating centers.

Subjects

Subjects with meniscal surgery of the right knee were selected from the OAI, excluding individuals with endstage OA of the right knee at baseline (baseline Kellgren-Lawrence (KL) grade higher than 3) and a history of rheumatoid arthritis. Individuals with multiple meniscal surgeries or ACL reconstruction were also excluded. The remaining subjects were categorized into 2 groups according to their reported history of preceding knee injury (badly enough to limit ability to walk for at least two days). For subjects with preceding knee injury, the follow-up question “Was this meniscal surgery performed to repair an injury episode?” was also part of the selection and needed to be answered as “yes”. To obtain a clear association of knee injury and meniscal surgery, we included only subjects who had meniscal surgery within 2 years after an episode of knee injury [8; 10]. In total, 158 subjects with preceding knee injury and 73 without were selected.

During the image analysis, 23 subjects showed severe meniscal deformity of the right knee, such as root or flap tears, severe extrusion or maceration. Since this would limit the meniscus scoring [27] and may have an independent impact on accelerating knee degeneration [28; 29], these subjects were excluded from the analysis. Subjects with bilateral meniscectomy of the right knee were also excluded due to the small number (n=3). To validate the score, we used the contralateral meniscus of the left knee as a reference [20; 30] and therefore excluded 70 subjects with meniscectomy or meniscal deformity with or without tears of the left knee at baseline. Using the above criteria, a total of 95 subjects with preceding injury and 40 without were selected as shown in Figure 1. All subjects had undergone meniscal surgery on average14 years (median 9 years, range 0-59 years) before baseline assessment and then were followed over an additional 48 months.

MR imaging

MR images were obtained at the four different clinical sites of the OAI with cross calibrated 3.0-T imagers (Trio, Siemens) using quadrature transmit-receive coils (USA Instruments). Images obtained with the following three sequences were analyzed: *(a)* coronal 2D intermediate-weighted (IW) turbo spin-echo (TSE) sequences [repetition time (TR)/echo time (TE), 3700 milliseconds (ms)/29ms]; (*b*) sagittal 2D IW TSE sequences with fat suppression (TR/TE, 3200ms/30ms); and *(c)* sagittal 3D dual-echo steady-state (DESS) sequences (TR/TE/flip angle, 16.3ms/4.7ms/25°). More details are available in the OAI MR protocol [31].

Meniscus resection score (MenRS)

A consensus training session was performed by three musculoskeletal radiologists (D.S., J.N. and T.M.L.) to calibrate and standardize readings. Subsequently, the amount and location of meniscal resection were scored on baseline MR images of the right knee by a radiologist (D.S.). As shown in Figure 2, a zone classification system modified from Cooper et al [32] was used. Each meniscus was divided into radial and circumferential zones, each comprising one-third of the meniscus. Radial zones were referred to as A, B, and C for the medial meniscus (from posterior to anterior) and D, E, and F for the lateral meniscus (from anterior to posterior). The circumferential zones were 1 for the inner third, 2 for the middle third, and 3 for the outer third. The anterior and posterior horn were typically assessed in the sagittal plane of MR images, whereas the body of the meniscus was assessed in the coronal plane [33]. To avoid overlap between grades obtained in the different planes during our analyses we cross-referenced the grades using the thin section axial multi-planar reformatting of the sagittal 3D DESS sequence, which allows better assessment of shape and subdivisions of the entire meniscus [21].

To evaluate the amount of meniscus resected, each zone was graded either as 0 (no resection), 1 ($<$ 50% of the area resected) or 2 ($>$ 50% of the area resected) as shown in Figure 3 and then summed across zones. The maximum value of MenRS for each meniscus was 18, which is consistent with near total meniscectomy. To validate the MenRS concerning the amount of meniscal resection, findings were compared with the contralateral meniscus, which was used as a reference [20; 30].

WORMS grading

Baseline and 48-month follow-up images of the right knee were graded semi-quantitatively to assess fairly early knee degenerative changes, using the modified Whole Organ Magnetic Resonance Imaging Score (WORMS) system [34]. To optimize reproducibility in the grading, all members in our group initially have to undergo a WORMS training. In this study, a trained radiologist (D.S.), blinded to subject characteristics, scored all MRIs under the supervision of a board certified musculoskeletal radiologist (T.M.L.). Cartilage defects were scored from 0 to 6, bone marrow edema pattern (BMEP) as well as subarticular cysts were scored from 0 to 3 in each of the same six regions (patella, trochlea, medial/lateral femur, and medial/lateral tibia). Other abnormalities including those of the ligaments and joint effusion were also graded. Since meniscal surgery was our predictor, we did not include meniscal lesions as one of the outcomes. We calculated sum scores combining all five imaging parameter categories as well as for each imaging category individually over all sub-regions of each knee.

Reproducibility

Two radiologists (D.S., J.N.) independently graded meniscal resection in 20 randomly selected subjects to determine inter-reader reproducibility. After a 1-month interval, the grading was repeated to determine intra-reader reproducibility. Intra- and inter-reader reproducibility of the amount of meniscal resection were assessed by the intra-class correlation coefficients (ICCs) and the Bland-Altman plots.

Statistical analyses

Statistical analyses were performed with STATA (Version 14; Stata, College Station, Tex), using a two-sided, 0.05 level of significance. Subject characteristics were calculated separately in subjects with and without preceding injury. Between-group differences were assessed by Student's independent t-tests or chi-square tests as appropriate. Regression models and partial correlations were used to assess the associations of MenRS with baseline WORMS grades and change in WORMS grades (independent variable: MenRS, dependent variables: mean baseline WORMS parameters and mean increase in WORMS grades over 48 months). Linear regression models were used with numeric dependent variables (i.e. total WORMS grades as well as cartilage, BMEP, cysts and ligaments subscales) while logistic regression models with binary dependent variables (i.e. the presence of effusion).

Since previous studies have highlighted that knee OA following meniscectomy is primarily found at the tibiofemoral joint [14; 35], four separate compartmental predictors were examined for cartilage defects, BMEP and subchondral cysts: index compartment (surgical tibiofemoral joint), contralateral compartment (nonsurgical tibiofemoral joint), femoral compartment (lateral and medial femur) and tibial compartment (lateral and medial tibia).

In a subsequent analysis, we examined whether the occurrence of a preceding injury confounded the relationship between MenRS and WORMS grades by including injury as a covariate. All analyses were adjusted for age at baseline, age at surgery, sex and baseline BMI.

Results

Subject characteristics

Subject characteristics are shown in Table 1. No significant differences were found between subjects with and without preceding injury except for the mean age at surgery, which was significantly higher in subjects without preceding injury compared to those with preceding injury (51.7±12.0 years vs 41.2±15.4 years, p<0.001).

Validation using the contralateral side as a reference

Comparing the corresponding menisci of the resected right knee and the control left knee, differences in meniscal morphology were found in 96 of 135 menisci and all of these knees had a meniscal resection with MenRS=1-18. Even after review with the contralateral side no differences in meniscal morphology were found in 39 subjects. In these menisci, resection or debridement may have been minimal, which was not visualized with MRI, and therefore we scored them as MenRS=0. In these 39 subjects cartilage in the tibiofemoral compartment was found to be significantly less damaged at baseline than in those 96 subjects with meniscal resection grade 1-18 (2.31±2.41 versus 4.79±4.48, coefficient: 2.94, p<0.001) but longitudinal change over 48 months was not significantly different (p>0.05).

Scoring amount of meniscus resected

The amount and location of the resected meniscus, assessed with the proposed method on baseline MR images are demonstrated in Table 2. Of the 96 subjects with MenRS>0, the mean score in subjects with preceding injury was found to be significantly higher compared to those without preceding injury (7.83 ± 6.21 vs 5.01 ± 3.65, p=0.03). In addition, scores ranging from 16 to 18, representing a resection of most meniscal tissue, were significantly more often present in subjects with preceding injury compared to those without preceding injury (16.8% vs 2.5%, p=0.02).

Reproducibility

ICCs for intra- and inter-reader agreement of MenRS in the overall meniscus were 0.980 (95% CI: 0.949, 0.992) and 0.977 (95% CI: 0.941, 0.991), respectively. In the Bland-Altman plots of intra- and inter-reader assessments, most of the values ranged within a mean difference ± 1.96 SD of -0.15±2.72 and -0.05±2.95, respectively (Figure 4). Furthermore, intra-reader ICCs of MenRS in anterior horn, body and posterior horn were 0.992, 0.968 and 0.966, while inter-reader ICCs were 0.998, 0.963 and 0.905. For WORMS gradings, the inter-reader reliability was good with ICCs of 0.876-0.919 for cartilage defects, BMEP and cysts, as assessed during the training.

Association between amount of meniscus resected and degenerative disease burden

Significant associations were found between amount of meniscus resected and baseline WORMS grades, with higher MenRS being associated with higher WORMS grades (Table 3, Figure 5). The MenRS were significantly associated with total WORMS for all five MR imaging parameter categories (r=0.25, p=0.004), as well as separately for cartilage (r=0.25, p=0.004) and ligaments (r=0.32, p<0.001), but not for BMEP, subchondral cysts and joint effusion (odds ratio: 1.01, 95% CI: 0.92-1.10, p=0.86).

In separate analyses of index and contralateral compartments, the MenRS showed significant correlations with baseline total WORMS, cartilage lesions and BMEP in the index compartment (r range 0.33-0.37, p≤0.001), while no or only weakly significant correlations were found in the contralateral compartment (r range 0.18-0.21, p range 0.049-0.09). With respect to the femoral and tibial compartments, the correlations between MenRS versus baseline cartilage lesions and BMEP were both statistically significant (femoral, r range 0.33-0.36, p<0.001; tibial, r range 0.43-0.49, p<0.001).

However, the MenRS was not significantly associated with changes in WORMS grades over 48 months, except for BMEP of the index compartment (r=-0.25, p=0.03). After further adjustment for preceding knee injury, the associations of MenRS with baseline WORMS and change in WORMS grades remained nearly the same (Supplemental Table). Assessing clinical features, the MenRS did not show significant associations with the baseline Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores as well as change in WOMAC scores over 48 months (linear regression, p-range =0.27-0.95).

Discussion

In this study, we developed an MR-based semi-quantitative scoring method to assess the amount of meniscus removed in patients that underwent meniscectomy. The score showed excellent intra- and inter-reader reproducibility and was significantly associated with severity of postoperative knee OA using cross-sectional WORMS analysis. However, there was no significant association between the MenRS and WORMS change scores between baseline and 48-month. Furthermore, the association of MenRS with WORMS grades did not vary when further adjusted for preceding knee injury, though larger resections were found after previous injury.

Standard partial meniscus resection procedures like shaving or debridement make the exact measurement of the resected meniscal volume challenging [20]. To date, two approaches have been published for assessing meniscal resection. The International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine Knee Committee recently proposed for surgeons to calculate the percentage of resected meniscal surface area on a diagram created after reviewing operation records; however, this approach was found to be only moderately reliable

(ICC=0.65) [36]. Bowers et al validated a quantitative MRI approach for detecting a decrease in meniscal volume due to partial resection [19; 20]. Nevertheless, the time required for meniscal segmentation by different techniques varied between 30 and 90 minutes [21; 34; 37]; and its validity in detecting a small amount of resection was questioned, especially for patients with meniscal hypertrophy [29].

The proposed scoring method offers a novel way to evaluate the degree of resection after meniscectomy using routine knee MRIs. The zone classification of meniscal resection in our method was based on Cooper's classification system that has been widely used to standardize description of meniscal tears and guide surgical treatment [32; 36]. Using the menisci of the contralateral knee as a reference our approach showed excellent performance. The evaluation of the amount of the resected meniscus on a 3-point scale for each zone was concise and simple with 5-7 minutes required for a musculoskeletal radiologist to score each knee. The comparison with the contralateral knee only added approximately 2 minutes.

The intra- and inter- reproducibility for the MenRS detected amount of resection per meniscus, and even per radial zone, were excellent. The MenRS showed significant positive associations with total WORMS as well as cartilage and ligament sub-scores, indicating that a larger amount of meniscal resection was associated with a higher number of knee osteoarthritic abnormalities. Biomechanical studies have repeatedly documented increases in contact stress and shear stress over articular cartilage, changes in pressure distributions and loss of joint stability with respect to the amount of meniscus resected [15; 38; 39]. These adverse effects potentially increase the susceptibility of cartilage to damage and place the knee at higher risk of OA development [40], in line with our findings. No significant correlations between MenRS versus BMEP and subchondral cysts were found. This may be related to the variability of BMEP over time and the strong association between BMEP and subchondral cysts as described previously [41; 42]. As expected, separate analyses showed that the MenRS was significantly associated with WORMS grades of the index compartment but not of the contralateral compartment.

When correlating MenRS with changes in WORMS scores over 48 months, no significant differences were shown in the majority of imaging parameter categories and compartments. However, these findings do not suggest that the amount of meniscal resection is not associated with the progression of knee OA after meniscectomy. Subjects in our study had undergone meniscal surgery an average of 14 years earlier. At baseline assessment, many subjects already had radiographic knee OA and substantial cartilage lesions. We hypothesize that progression of degenerative changes may occur soon after surgery and then plateau or decrease as the joint adjusts to the meniscal resection [5; 35].

Our findings confirmed the observation of Englund et al [17; 18] that subjects with preceding injury appeared to undergo meniscectomy at a younger age and had a higher rate of total resection compared to subjects without preceding injury. Several previous studies reported higher evidence of knee OA following resection of degenerative than traumatic meniscal tears [35; 43]. Conversely, Matsusue et al found no significant difference in clinical outcomes between patients with and without a history of trauma [3]. In our study, when determining the association of amount of meniscal resection and the severity of postoperative knee OA, we found no significant difference between subjects with and without preceding injury. These findings indicate that in patients with meniscal surgery the resection amount is likely the main risk factor for the subsequent knee joint degeneration, whereas the initial reason for meniscal resection seems to be subordinate.

Moreover, our proposed method could detect the part of the meniscus resected (lateral/medial, AH/body/PH). Subjects with a lateral meniscectomy sustained a significantly worse baseline WORMS outcomes in the global and index compartments when compared to those with medial meniscectomy. When investigating the association between side of resection and WOMAC scores, no significant differences were found between medial and lateral meniscus. However, the limited number of lateral meniscectomies in our study (baseline: n=14, 48-month: n=10) should be noted.

Our study has several limitations. Firstly, surgical reports of meniscectomy were not available for participants in the OAI dataset due to the HIPAA compliance. However, to ensure accuracy on the information about the participants' meniscectomy, we used the self-reported questionnaires to identify participants with meniscectomy and moreover, all MRIs were reviewed thoroughly by a musculoskeletal radiologist for signs of meniscal surgery. Secondly, baseline MRI scans were acquired with long interval following surgery, potentially not capturing important imaging findings occurring directly after meniscectomy. Finally, preoperative MRIs are more readily available in clinical trials and would be helpful for further investigating the type of meniscal tears [17]. In our study, we utilized contralateral knee MRIs and found them to be a reliable reference. Of further note was that the index (right) knee showed significantly higher WOMAC scores both at baseline and 4-year FU when compared to the contralateral (left) knee, which was in line with previous studies finding that radiographic OA was substantially more frequent in the operated knee than in the contralateral knee [44, 45].

In conclusion, the described MR-based semi-quantitative scoring method is a concise and reproducible technique for assessing various degrees of partial meniscectomy and the score is significantly correlated with the severity of postoperative knee OA. Subjects had an increased risk of cartilage defects, BMEP and ligamentous abnormalities with increased meniscus resection, particularly in the index compartment.

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Table Legends

Table 1. Subject characteristics

Table 2. MR-based semi-quantitative scoring of amount and location of meniscus resected

Table 3. Association of meniscus resection score with baseline WORMS and change in WORMS grades over 48 months [a]

Figure legends

Figure 1 Flowchart shows subject selection from OAI database.

Figure 2 Zone classification of the meniscus for scoring amount of meniscus resected.

Figure 3 Grading amount of meniscus resected for each involved zone. Schematic drawings (left) and MR images (right) show grade 1 < 50% (A) and grade 2 > 50% (B) of the subregional volume resected in the inner third of the body of medial meniscus (zone B1) in the right knee. The resected meniscal tissues, cross-hatched in schematic drawings, are noted as truncated appearance (arrow) in the coronal 2D intermediate-weighted turbo spin-echo sequence and substance loss (arrow) in the axial multi-planar reformatting of the sagittal 3D dual-echo steady-state sequence. The small MR images show the contralateral meniscus of the left knee which are used as a reference.

Figure 4 Bland-Altman plots showing (A) the difference between assessments by two readers, and (B) the difference between two occasionally different assessments by one reader.

Figure 5 Sagittal intermediate-weighted turbo spin-echo fat-suppressed MR images of the left knee at baseline (A, D), the right knee at baseline (B, E) and the right knee over 48 months (C, F). A-C show the MR images of a 45-year-old woman who had a knee injury and then underwent medial partial meniscectomy (arrows) (meniscal resection with a score of 4 at the posterior horn) when she was 30 years old. D-F show the MR studies of a 57-year-old man who had no knee injury and underwent partial meniscectomy (arrows) (meniscal resection with a score of 2 at the posterior horn) when he was 50 years old. The 45-year-old woman with a large amount of meniscal resection demonstrated a full-thickness focal cartilage defect at the medial tibia at baseline (thin arrows) (medial tibial cartilage WORMS grade 5); over 48 months, she developed BMEP at the medial tibia (*) (medial tibial BMEP grade 0 in B and 2 in C) and thinning of the cartilage at the medial femoral condyle (arrowheads) (medial femoral cartilage WORMS grade 0 in B and 3 in C). In contrast, only a partial thickness cartilage defect at the medial femur (arrowheads) was seen in the 57-year-old man with a relatively small amount of meniscal resection and no progression was detected over 48 months (medial femoral cartilage WORMS grade 3 in B and C).