Assessment of Persistent Meniscal Degeneration and Extrusion in Patients Following Intact Medial Meniscus Posterior Root Tear Repair with 3D T2* Mapping at 7 Tesla

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INTRODUCTION: The meniscus plays a vital role in providing joint stability, cushioning and shock absorption, distributing the load across the knee joint, and maintaining the long-term function and structural integrity of the joint[1,2]. It is primarily composed of collagen fibers, which anchor the meniscal tissue to the underlying bone through its root attachment. Medial meniscus posterior horn root tears (MMPRTs) are significant injuries that disrupt the continuity of collagen fibers, leading to meniscal extrusion and an increased risk of rapid progression to knee osteoarthritis[1,3]. Quantitative MRI, particularly T2 and T2* relaxation time mapping, has been associated with meniscus structural integrity, specifically collagen fiber network[3], and meniscal degeneration[4].
The goal of this study was to utilize high-resolution 7T 3D T2* mapping to longitudinally assess the medial and lateral menisci in patients with MMPRTs, both before root repair (pre-repair) and seven months after repair (post-repair), and to compare these findings with healthy controls. We hypothesize that the disruption of collagen fiber network caused by MMPRTs leads to increased T2* values and the T2* values will correlate with medial meniscus extrusion.

METHODS: This IRB-approved study involved 26 patients with a unilateral posterior root tear of the medial meniscus (mean age, 53 years ± 8 years; mean BMI, 28.6 kg/m2; 21 female) and nine healthy controls (mean age, 51 years ± 11 years; mean BMI, 26.2 kg/m2, 7 females). Each patient underwent the same MRI protocol twice on a 7T MRI system—once pre-repair and again post-repair—while the control group underwent a single scan. The MRI protocol included T1- and T2-weighted multi-slice turbo-spin echo (TSE) sequences and a T2-weighted 3D TSE (i.e. SPACE) with and without fat suppression. For quantitative assessment, a 3D multi-echo gradient recalled echo (GRE) sequence was acquired to calculate T2* relaxation time maps of the meniscus (repetition time (TR): 26 ms; seven echo times (TE): 3.1-21.4 ms; resolution: 0.4×0.4×1 mm^3; scan time: 5min:20s). The acquired multi-echo T2* data was used to fit a mono-exponential signal decay with a two-parametric least-square fitting routine in Matlab. To assess fitting accuracy, the root mean square error (RMSE) was normalized to the estimated signal intensity at the echo time of 0 ms. Manual 3D segmentation was performed on T2*-weighted images using ITK-SNAP (**Fig. 1**). For menisci with tears, the segmentation extended from 1 mm distal to the anterior root attachment to approximately 1 pixel (0.44 mm) proximal to the posterior root tear, while mirrored segmentation was performed on the controls. Segmented menisci were subsequently subdivided into four regions based on angles relative to the line connecting the anterior and posterior horns (**Fig. 1B**): i) anterior horn (0°- 45°), ii) anterior body (45°- 90°), iii) posterior body (90°- 135°), and iv) posterior horn (135°-180°). The median T2* values and the corresponding RMSEs were calculated in the four meniscal regions. Meniscal extrusion was evaluated on coronal T2-weighted images with fat suppression using two vertical lines at the peripheral margins of the medial tibial plateau and the outermost edge of the meniscal body. Kruskal-Wallis test and Spearman rank correlation (ρ) were used for statistical analysis.

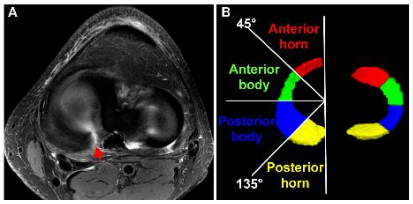

Figure 1. A) Axial T2-weighted image showing (arrow) medial meniscus posterior horn root tear (MMPRT). B) Reconstructed 3D segmentation masks of the medial (left) and lateral (right) menisci.

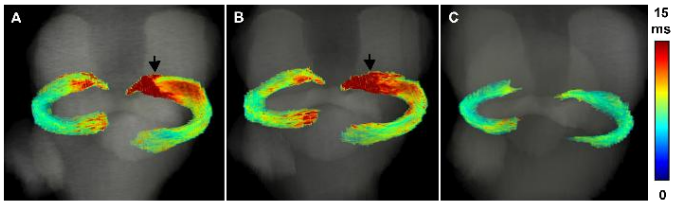

Figure 2. Representative 3D T2* maps of the medial and lateral menisci overlaid on segmented, semi-transparent femorotibial bone. (A) Pre-repair image of a patient with MMPRT (arrow), (B) post-repair image of the same patient, and (C) healthy control. Elevated T2* values are observed both pre- and post-repair proximal to the MMPRT.

RESULTS: Significantly longer T2* values were observed across medial and lateral menisci in both pre- and post-repair patients when compared to the controls ([medial meniscus: anterior body P< 0.05; anterior horn, posterior body and posterior horn all P< 0.01]; [lateral meniscus: anterior body and posterior body P< 0.05; anterior horn and posterior horn P< 0.01]). (**Figs. 2-3**). The highest differences between patients and controls were observed in the posterior body and posterior horn of the medial meniscus, which are proximal to the MMPRT. RMSE was below 5.7% for all regions, indicating good fitting performance. Additionally, meniscal extrusion was significantly increased (P = 0.002) in post-repair patients (4.9 ± 1.4 mm) compared with pre-repair patients (3.7 ± 1.1 mm). A strong correlation (ρ =0.676; p<0.001) was found between pre-repair T2* values and post-repair extrusion measurements.

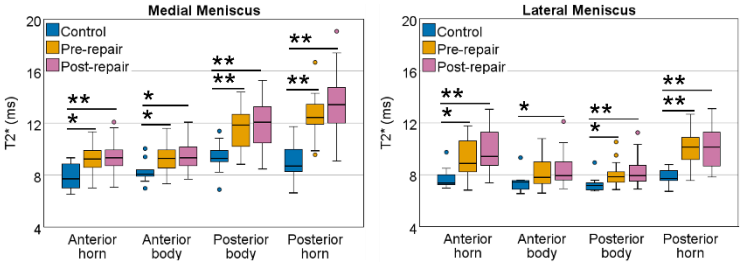

Figure 3. Boxplots of the T2* values comparing analyzed meniscal regions of patients with MMPRTs pre-repair and post-repair, and healthy controls. The T2* relaxation times in patients both pre- and post-repair were significantly longer (*P < .05; **P < .001) when compared to the controls across both menisci.

DISCUSSION: The persistently elevated T2* values in both pre- and post-repair patients reflect ongoing disruption of the collagen fiber network[4] beyond seven months following the surgical repair of the root tear[5]. Importantly, the findings also demonstrated a strong correlation between the meniscal T2* values and extrusion, underscoring the link between altered structural integrity and its impact on tissue laxity. In conclusion, 3D T2* mapping at 7T can detect persistent collagen fiber disorganization and predict postoperative meniscal extrusion in patients with medial meniscus posterior root tears.

SIGNIFICANCE/CLINICAL RELEVANCE: Persistently elevated T2* values, and increased extrusion postoperatively suggest delayed restoration of collagen matrix integrity, potentially requiring prolonged healing times. The findings are particularly significant for accurately monitoring meniscal healing and assessing structural integrity, as the success of surgical repair relies on evaluating quality of the meniscal tissue and ensuring the restoration of healthy tissue throughout the entire meniscus, including the repair site.

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