Three-dimensional reconstructed magnetic resonance scans: Accuracy in identifying and defining knee meniscal tears

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AIM
To determine whether three-dimensional (3D) reconstruction from conventional magnetic resonance imaging (MRI) is able to accurately detect a meniscal tear, and define the configuration.

METHODS
Thirty-three patients’ 3T MRI scan data were collected and sagittal uni-planar 3D reconstructions performed from the preoperative MRI. There were 24 meniscal tears in 24 patients, and nine controls. All patients had arthroscopic corroboration of MRI findings. Two independent observers prospectively reported on all 33 reconstructions. Meniscal tear presence or absence was noted, and tear configuration subsequently categorised as either radial, bucket-handle, parrot beak, horizontal or complex.

RESULTS
Identification of control menisci or meniscal tear presence was excellent (Accuracy: observer 1 = 90.9%; observer 2 = 81.8%). Of the tear configurations, bucket handle tears were accurately identified (Accuracy observer 1 and 2 = 80%). The remaining tear configurations were not...
accurately discernable.

CONCLUSION

Uni-planar 3D reconstruction from 3T MRI knee scan sequences are useful in identifying normal menisci and menisci with bucket-handle tears. Advances in MRI sequencing and reconstruction software are awaited for accurate identification of the remaining meniscal tear configurations.

Key words: Knee; Meniscus; Arthroscopy; Magnetic resonance imaging; Three-dimensional reconstruction; Materialise Interactive Medical Control System; Tear

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Core tip: Three-dimensional reconstruction from magnetic resonance imaging (MRI) is an expanding field with potentially great clinical utility, but must be applied with caution when segmenting knee meniscal tears. Tear presence or absence, and the complex configuration of bucket handle tears were accurately distinguishable. The remaining tear configurations could not be correctly identified. Advances in MRI sequencing and reconstruction software need to be made before the remaining meniscal tear configurations will be identifiable.

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INTRODUCTION

The knee menisci are vital to tibiofemoral contact mechanics 1-3 and joint longevity 4-6. Tears thereof are common injuries 7, occurring both as traumatic tears in younger patients and degenerate tears in older patients 8-10. Traumatic tears may adopt several different configurations 11, depending predominantly upon the mechanism and extent of injury. By contrast, degenerate tears occur mainly as cleavage tears along the horizontal plane in which myxoid meniscal degeneration is known to occur 12,13. This variation in tear configuration and extent affects surgical planning regarding reparable or resection, and thus patient management. Accurate preoperative diagnosis is therefore important. Currently magnetic resonance imaging (MRI) is commonly used to preoperatively diagnose a meniscal tear. This however relies heavily on specialist radiological interpretation for diagnosis and adds further burden to a loaded service. Three-dimensional (3D) reconstruction from the MRI presents the data as a single alternative image for analysis. Interpretation of meniscal pathology in this 3D reconstructed meniscus is potentially simpler, as presentation of image data in three dimensions allows for better spatial relationship appreciation, easier object manipulation to view in any plane, and lessens the inferential burden on the observer.

3D meniscal reconstruction has accurately demonstrated meniscal dynamics relative to the tibial plateau 12,14 and shown encouraging results in tear delineation, suggesting that 3D reconstruction may be particularly beneficial in showing up radial and horizontal tears not visible on the 2D MRI 15. Meniscal reconstruction has previously been used to investigate tibiofemoral contact 16-18, and in calculating pre-and post-meniscectomy meniscal volumes 19. With current advancement in 3D reconstruction technology, this study aimed to determine whether 3D reconstruction of meniscal tears using current MRI protocols could accurately identify meniscal tears, and define their configuration.

MATERIALS AND METHODS

Study design

Cross sectional clinical cohort study.

Sample population

First the five common meniscal tear types were identified and categorised in groups as either radial, bucket handle (longitudinal displaced), parrot beak (oblique), cleavage (horizontal) and complex tears. Following, the operative notes of all arthroscopies undertaken on adult patients (aged over 18 years) by two experienced consultant orthopaedic surgeons at our institution were retrospectively reviewed to gather a minimum of five meniscal tears in each tear category. A further five normal menisci, defined at arthroscopy as having no tear or degeneration, were identified for each surgeon.

Subsequently the scans from these patients with the various tear configurations were retrieved for segmentation. In all cases arthroscopy was performed after preoperative MRI had indicated a potential meniscal tear. All preoperative scans were performed on a 3T MRI scanner (Philips) and reports on each by a subspecialized consultant musculoskeletal (MSK) radiologists were collected. Due to MRI data recording errors and one patient duplication, the final study population consisted of 24 meniscal tears in 24 patients, and nine control menisci.

MRI features

For all cases, imaging at 3T, and using a Philips Sense extremity Knee Coil, Fast Spin Echo (FSE) sequences were used to obtain Proton Density (PD) Fat Saturated images in the sagittal, coronal and axial planes. Following, a Gradient Recall Echo (GRE) sequence was employed to again image in the sagittal plane. The Time to Repetition (TR) varied from approximately 845 ms (for the GRE) to approximately 2500-7400 ms (for the PD). The Time to Echo (TE) varied from approximately 9 ms (for the GRE) to 30 ms (for the PD). The imaging characteristics were a Field of View (FOV) of 16 cm × 16 cm; a slice thickness of 2-3 mm; an...
interslice gap of between 2-3.3 mm; a matrix of either 512 \times 512 or 1024 \times 1024 and an Echo Train Length (ETL) of 14.

3D reconstruction
All patient MRI data for the 3T scans were imported into the Materialise Interactive Medical Control System (MIMICS) 3D reconstruction software program (Materialise, Leuven, Belgium) for subsequent reconstruction. All 33 scans were reconstructed from sagittal plane images by the lead author, segmenting both menisci for each knee scanned. This final image was then “wrapped” and stored as a finite element model for future interpretation. Each reconstruction was time consuming, taking approximately 4 h to generate the final model. In order to minimize the inaccuracies in the segmentation and reconstruction, the lead author undertook a two-day training course by the Materialise staff in using the novel software. Further, each reconstruction was reviewed for error in segmentation by a subspecialised MSK radiologist, and the adjacent uninjured meniscus reconstruction served as an innate control (Figure 1).

3D image analysis
Two orthopaedic trainees, who were both familiar with the different types of meniscal tears, reported on the reconstructions. Prior to reporting, each observer received a separate training session using this new software and were made familiar with user functions and object manipulation, as well as normal and meniscal tear appearances in 3D. Each training session took no longer than ten minutes, as the user functions to zoom or pan and manipulate the image to view it in any desired plane are intuitive and easy to reproduce. There was hence no learning curve associated with this as the execution of each function is binary, and each surgeon was equipped with all the functions prior to undertaking the reporting.

Both trainees were blinded to the preoperative MRI and operative findings, and were blinded as to the number of tears in each configuration category. All 33 meniscal reconstructions were then brought up in random order in the MIMICS software program for independent reporting. Each observer prospectively reported their findings on a standard pro forma. Inter-observer and intra-observer repeatability were determined. Two primary assessments were made. First, tear presence vs absence was determined and subsequently the meniscal tear configuration was calculated (Figure 2).

RESULTS
Study population characteristics
Thirty-three patients were included in the final study, 20 were male and 13 were female. There were 14 tears in right knees and 10 tears in left knees. The 9 control patients consisted of 8 right knees and 1 left knee. Nineteen tears were in the medial meniscus and five tears were in the lateral meniscus. The mean time between

![Figure 1: The user interface of the Materialise Interactive Medical Control System segmentation software program depicting the coronal view (A), the axial view (B), the sagittal view (C) and the three-dimensional reconstruction view (D). Note the poorer contrast and pixelated images in coronal and axial windows as compared the sagittal window.](image-url)
MRI and arthroscopy was 4 mo (Range 1 mo to one year). All cases had arthroscopic validation of their tear configuration.

Results for all reconstructions
The accuracy and predicative values for detecting the presence or absence of a meniscal tear, regardless of tear configuration, were as follows.

Observer 1: The values for detecting tears presence vs absence were: Sensitivity 91.7%, specificity 88.9%, PPV 95.7%, NPV 80.0%, and accuracy 90.9%.

Observer 2: The values for detecting tears presence vs absence were: Sensitivity 87.5%, specificity 66.7%, PPV 87.5%, NPV 66.7%, and accuracy 81.8%. Both the intra- and inter-observer computed Cohen’s Kappa = 0.525, indicating a moderate degree of agreement.

Results for each meniscal tear configuration
Sub-classification for each tear configuration was then calculated for each observer: (1) Observer 1: Accuracy for detecting different tear configurations (Table 1); (2) Observer 2: Accuracy for detecting different tear configurations (Table 2).

As can be seen when comparing these results of the 3D reconstructions by meniscal tear configuration with those obtained on 2D MRI sequences from the literature in the table below, only the detection of bucket handle tears compares favourably (Table 3).

Morphological similarities
Morphological similarities, particularly in 3D reconstruction, between certain tear types exist. As evident from the
reconstructions, the primary similarities are observed in the parrot beak and radial configurations, and the complex and cleavage tear configurations. Interestingly, when combining each into a single category, the sensitivities rivaled those of the normal and bucket handle tear configurations.

**Observer 1:** Accuracy when combining parrot beak and radial tears (7 of 11, 63.6%), and complex and cleavage tears (6 of 8, 75%).

**Observer 2:** Accuracy when combining parrot beak and radial tears (7 of 11, 63.6%), and complex and cleavage tears (7 of 8, 87.5%).

**DISCUSSION**

The MR diagnosis of a meniscal tear relies both on signal contrast and morphology. In un- or minimally displaced tears, the fluid entering the tear provides the contrasting signal with the surrounding normal meniscus, enabling the diagnosis. In severely displaced tears, the abnormal morphology of the meniscus is the key factor, indicating a tear is present. With 3D reconstruction from the MRI, these signal contrasts are utilised to provide distinct borders during the segmentation process to highlight out the meniscus, leaving only the morphology to interpret. Theoretically then, if the increased signal is seen on the 2D images, it should be reflected in the 3D reconstruction, enabling simpler diagnosis of tear presence and morphology.

In identifying meniscal tear presence or absence, the accuracies, sensitivities and specificities, as well as positive and negative predicative values in this study were equal to those obtained from 2D MRI\(^{18-20}\). Advantages of the 3D reconstruction however include presenting the MRI data in a visuospatially simple format and enabling object viewing in any plane to aid pathological identification. Further, it does not rely on radiologic skill or significant experience for interpretation.

Investigating by meniscal tear configuration, 3D reconstruction appeared useful in identifying normal menisci (Observer 1: Accuracy = 90.9%; Observer 2: Accuracy = 81.8%), and the complex configuration of bucket handle tears (Observer 1: Accuracy = 80.0%; Observer 2: Accuracy = 80.0%). However it had a lower accuracy in determining the remaining meniscal tear configurations.

Currently the achievement of adequate fine detail in 3D reconstruction enabling differentiation between morphologically similar tears is not possible using the present standard scan protocols. As can be seen when combining the morphologically similar tears above, the accuracy rivaled that achieved for the bucket handle tear configuration. Obscurations of meniscal tear border definition arise due to inaccuracies in the MRI, and in segmentation. MRI inaccuracies may be attributed to inherent magnetic field inhomogeneities, volume averaging and limited contrast dependent on the signal-to-noise ratio (SNR) maintainable across the FOV. Presently segmentation remains user dependent, time consuming and MRI quality reliant. Accurate tear and meniscal edge definition is still user defined, despite some semi-automated functions facilitating simpler and more efficient segmentation. While these inaccuracies are present, it is not possible to accurately determine meniscal tear extension to the periphery, this having clinical implication on prediction of healing whether or not the tear extends to the white-red zone or not.

Minimising these inaccuracies will increase the MRI quality, and hence the meniscal tear definition in 3D reconstruction. The greatest accuracy minimisation

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**Table 1** Observer 1’s meniscal tear configuration identification accuracy for all types of tear identified

| Tear Configuration | Number of each correctly identified | Accuracy |
|-------------------|-----------------------------------|----------|
| Bucket handle     | 4 of 5                            | 80%      |
| Radial            | 1 of 6                            | 16.7%    |
| Cleavage          | 3 of 5                            | 60%      |
| Parrot beak       | 2 of 5                            | 40%      |
| Complex           | 1 of 3                            | 33.3%    |

**Table 2** Observer 2’s meniscal tear configuration identification accuracy for all types of tear identified

| Tear Configuration | Number of each correctly identified | Accuracy |
|-------------------|-----------------------------------|----------|
| Bucket handle     | 4 of 5                            | 80%      |
| Radial            | 3 of 6                            | 50%      |
| Cleavage          | 3 of 5                            | 60%      |
| Parrot beak       | 1 of 5                            | 20%      |
| Complex           | 2 of 3                            | 66.7%    |

**Table 3** The sensitivities for meniscal tear type detection for previous studies utilizing 2D magnetic resonance imaging as compared to the authors’ results using the 3D reconstruction of meniscal tears

| Tear Configuration | Sensitivity (2D MRI) | Sensitivity (3D MRI) |
|--------------------|----------------------|----------------------|
| Radial             | 8 of 11 (72.7%)      | 3 of 5 (60.0%)       |
| Cleavage           | 26 of 36 (72.2%)     | 2 of 2 (100.0%)      |
| Parrot beak        | Jee et al\(^{27}\)    | Kruger N et al\(^{1}\) |
| Complex            | 25 of 39 (64.1%)     | 18 of 22 (81.8%)     |

| Tear Configuration | Sensitivity (2D MRI) | Sensitivity (3D MRI) |
|--------------------|----------------------|----------------------|
| Radial             | 8 of 11 (72.7%)      | 3 of 5 (60.0%)       |
| Cleavage           | 26 of 36 (72.2%)     | 2 of 2 (100.0%)      |
| Parrot beak        | Wright et al\(^{26}\) | The present report   |
| Complex            | 25 of 39 (64.1%)     | 18 of 22 (81.8%)     |

\(^1\)No such tear configuration specified in the study.
would be achieved by eliminating the volume averaging occurring due to the interslice gaps in current clinical knee MRI sequences. Current clinical MRI knee scan protocols leads to three separate image series, only one of which may be imported and 3D reconstructed at a time. This leads to uni-planar reconstruction, as the interpolated images in the remaining two imaging planes are very pixelated and of poor quality.

Adopting an isotropic volume scan protocol for clinical knee MRI scanning eliminates the interslice gaps, as the whole volume is scanned simultaneously, producing true 3D MRI. Recently this has been investigated as an alternative to conventional knee scanning protocols, with comparable results obtained in a shorter scanning time. This has a great impact on 3D reconstruction, as the whole data volume is imported, resulting in equivalent contrast in all three-image window planes, allowing tri-planar 3D reconstructions. This tri-planar reconstruction is anticipated to have finer meniscal tear and border definition, increasing the accuracy in differentiating between the morphologically similar tears.

There are some limitations, both of the study and the practical applicability of the reconstructions, that merit discussion. The time consuming nature of the reconstructions mean that only a low number could be generated and this limits the robustness of the conclusions drawn. It also means that the real time clinical use of being able to present the 3D model on screen to the patient, however much it might aid understanding and appreciation of their pathology, is not presently possible. The time between the MRI and arthroscopy was significant, and the potential for tear propagation or alteration of configuration exists. All patients however had arthroscopic corroboration of their MRI findings, so, for this patient cohort, there were no alterations in tear configurations, inaccurate tear assessment or false positive or negative diagnoses. Further, no differentiation between traumatic and degenerative tears was made. Although the pathophysiologcal processes that underpin these two tear types are distinct, as their diagnosis still relies on the separation of the tissue planes at the joint surface with synovial fluid entering the gap and altering the MR signal, this was deemed insignificant.

Lastly, longitudinal undisplaced tears were not included as one of the configurations for assessment, as the postulate was that being undisplaced, there would be too narrow a signal change for the 3D reconstruction to be able to accurately pick up the tear.

In conclusion, uni-planar 3D meniscal tear reconstruction is useful in identifying normal menisci and menisci with bucket handle tears. It however is unable to accurately report the remaining meniscal tear configurations. Significant technological advances need to be made in both MRI and 3D reconstruction, to rival 2D MRI diagnostic accuracy in defining meniscal tear configurations.

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