Original Investigation

Automated T2-mapping of the Menisci From Magnetic Resonance Images in Patients with Acute Knee Injury

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Abbreviations and Acronyms

MM medial meniscus
LM lateral meniscus
MR magnetic resonance
TSE turbo spin echo
DSI Dice similarity index
OA osteoarthritis
ACL anterior cruciate ligament
ICC intraclass correlation coefficient

Rationale and Objectives: This study aimed to evaluate the accuracy of an automated method for segmentation and T2 mapping of the medial meniscus (MM) and lateral meniscus (LM) in clinical magnetic resonance images from patients with acute knee injury.

Materials and Methods: Eighty patients scheduled for surgery of an anterior cruciate ligament or meniscal injury underwent magnetic resonance imaging of the knee (multiplanar two-dimensional [2D] turbo spin echo [TSE] or three-dimensional [3D]-TSE examinations, T2 mapping). Each meniscus was automatically segmented from the 2D-TSE (composite volume) or 3D-TSE images, auto-partitioned into anterior, mid, and posterior regions, and co-registered onto the T2 maps. The Dice similarity index (spatial overlap) was calculated between automated and manual segmentations of 2D-TSE (15 patients), 3D-TSE (16 patients), and corresponding T2 maps (31 patients). Pearson and intraclass correlation coefficients (ICC) were calculated between automated and manual T2 values. T2 values were compared (Wilcoxon rank sum tests) between torn and non-torn menisci for the subset of patients with both manual and automated segmentations to compare statistical outcomes of both methods.

Results: The Dice similarity index values for the 2D-TSE, 3D-TSE, and T2 map volumes, respectively, were 76.4%, 84.3%, and 75.2% for the MM and 76.4%, 85.1%, and 76.1% for the LM. There were strong correlations between automated and manual T2 values ($r_{MM} = 0.95$, $ICC_{MM} = 0.94$; $r_{LM} = 0.97$, $ICC_{LM} = 0.97$). For both the manual and the automated methods, T2 values were significantly higher in torn than in non-torn MM for the full meniscus and its subregions ($P < .05$). Non-torn LM had higher T2 values than non-torn MM ($P < .05$).

Conclusions: The present automated method offers a promising alternative to manual T2 mapping analyses of the menisci and a considerable advance for integration into clinical workflows.

Key Words: Magnetic resonance imaging; knee menisci; T2 Mapping; segmentation; T2 relaxation; acute injury; image processing.

INTRODUCTION

Meniscal degeneration, by altering normal knee function and loading mechanisms, has been identified as a strong determinant within the multifactorial etiology of knee osteoarthritis (OA) (1,2), and overall healthy and properly functioning menisci are paramount to the long-term health of the knee joint (3). These cartilaginous structures can be altered acutely via trauma or chronically through degenerative processes commonly found in knee OA or secondary to anterior cruciate ligament (ACL) injuries (4). Direct injuries often result in visible morphological alterations; however,

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such changes may not be obvious in the early stages of degenerative processes where biochemical alterations occur first (5–7). In both cases, quantitative magnetic resonance (MR) imaging of the meniscus could be useful for accurate diagnosis, surgery planning and follow-up, and for the early detection of degeneration not resulting in macroscopic tissue damage (5–8).

The acquisition of multiple multiplanar two-dimensional (2D) turbo spin echo (TSE) MR images is the standard clinical MR protocol for noninvasive assessment of the menisci. In research studies, three-dimensional [3D]-TSE and T2 mapping MR imaging have been shown to provide enhanced morphological and biochemical assessment of soft tissue structures including the menisci (9–17). In both cases, the identification of the menisci volume in the images remains challenging and a major obstacle to clinical integration of quantitative MR imaging. Subjective manual or semiautomated segmentations are currently the primary means to analyze the structures in the MR images. These methods are time- and expertise-intensive and associated with variable intra-rater and inter-rater reliability for subsequent measurements (18), hence limiting their utility in clinical workflows.

In recent years, a limited number of automated solutions for segmentation of the knee menisci have been developed (19–23). At this stage, these have only been shown to provide accurate segmentations for the healthy menisci (21,22) or for pathological subjects using nonroutine research sequences requiring prohibitively long scan times for clinical applicability (eg, dual-echo steady-state MR images) (23). Evaluating the performance of automated segmentation and analysis of the damaged menisci using routine clinical MR protocols is desirable but currently unknown.

Biochemical T2 maps are not well suited for direct segmentation of the menisci owing to the limited contrast between the menisci, cartilages, and ligaments, and a large slice thickness (usually 2–4 mm). Alternatively, routine 2D-TSE or newer 3D-TSE MR sequences provide better tissue contrast and spatial resolution (3D-TSE) and may prove advantageous for accurate automated segmentations of the meniscus.

The objective of this study was to evaluate the performance of a deformable model and registration-based method for the automated segmentation and T2 analysis of the menisci from several routine clinical MR sequences (2D or 3D-TSE and T2 maps) acquired from a clinically relevant cohort of patients undergoing surgery for isolated acute meniscal or ACL injury or combined acute meniscal and ACL injury.

MATERIALS AND METHODS

Study Population

The current study included 80 patients (38 women, 42 men) with a mean age of 31 years (18–82 years) who had a 3T MR examination up to 90 days before arthroscopic surgery for treatment of an acute ACL injury, acute meniscus injury, or an acute combined ACL and meniscal injury (11 days average between MR imaging and arthroscopy). These patients were classified into three injury groups (as identified at arthroscopy): (1) acute ACL injury (ACL_i, $N = 22$), (2) acute meniscus injury (MEN_i, $N = 11$), and (3) combined acute ACL plus meniscal injury (COM_i, $N = 47$). The study was conducted between December 2011 and April 2014, was approved by the institutional review board at (the Vail Valley Medical Center), and all subjects provided informed consent.

MR Imaging

All images were acquired on a Siemens Verio 3.0 Tesla scanner (Siemens Medical Solutions, Erlangen, Germany) with a gradient strength of 40 mT/m using a 15-channel multielement phased-array knee coil (Quality Electrodynamics LLC, Mayfield, OH). Patients were positioned supine during the acquisition, with the knee centered in the coil. For each patient, a sagittal multi-echo spin echo T2 map was acquired for biochemical MR assessment, and either (1) sagittal, coronal, and axial 2D fat-suppressed proton density TSE MR images ($N = 37$) as per current standard clinical knee examinations or (2) single fat-suppressed proton density 3D-TSE MR images (isotropic with enhanced multiplanar reformatting (24), $N = 43$) were acquired. The MR parametric T2 maps were generated from seven different echo times using the syngo MapIt online reconstruction software provided by the vendor (Siemens Medical Systems). The parameters of the MR sequences are provided in Table 1. All datasets used for analyses were anonymized.

Manual Image Analysis

A subset of MR examinations from 31 patients ($N_{2D\text{-}TSE} = 15$, $N_{3D\text{-}TSE} = 16$) was blindly selected for baseline manual segmentation and analysis of the meniscus. To obtain results from both injured and non-injured menisci, half were randomly selected in the ACL_i group and half were randomly selected in the COM_i group. For each of the selected patients, the medial meniscus (MM) and lateral meniscus (LM) were manually segmented in the sagittal plane of the 3D-TSE or sagittal 2D-TSE MR images and in the second echo of the T2 maps by two experienced musculoskeletal analysts using an interactive touch screen drive with stylus (Carly Lockard using Mimics [Materialize Inc., Plymouth, MI] and Mark Strudwick using ITK-Snap (25)). The expert analysts agreed on segmentation conventions and manually segmented a 3D-TSE MR image in common. After consensus regarding the resulting meniscus volumes, each analyst manually segmented half of the selected data. For better definition of the meniscus and peripheral tissues in areas of tissue ambiguity, morphological 3D-TSE and 2D-TSE images were viewed side by side with the T2 maps to guide segmentations. The segmentation of both the MM and the LM in a single 2D-TSE, 3D-TSE, and T2 map MR image required 120 minutes, 60 minutes, and 120 minutes, respectively. The expert segmenters were blind to the automated segmentation method.