The Unique Anatomical Feature of the Discoid Lateral Meniscus in a 3-dimensional MR Image

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Abstract

Background: Discoid lateral meniscus (DLM) represents a distinctive anatomical variation characterized by a larger and thicker lateral meniscus. For the clinical diagnosis of DLM, coronal and sagittal slices in 2-dimensional (2D) magnetic resonance imaging (MRI) and arthroscopic imaging have been used. However, it is difficult to evaluate the entire shape of the DLM owing to its limited views and details. 3-dimensional (3D) visualization using MRI has been used to visualize the entire meniscus. The purpose of this study was to demonstrate the entire shape of a DLM using 3D images and unveil its unique characteristics.

Methods: The study population consisted of 31 consecutive knees with DLM, diagnosed arthroscopically in our hospital, between 2017 and 2021 and 43 consecutive knees without DLM as a control population. 3D images of the medial meniscus (MM) and lateral meniscus (LM) were reconstructed from 1.5T-MRI images with semi-automatic segmentation using the free software. From the coordinate information, the anterior-to-posterior lengths of the MM and LM were obtained, and the ratio of the medial to lateral anterior-to-posterior length (L/M ratio) was calculated and compared with the value of the non-DLM population.

Results: Our method enables the delineation of the entire morphology of the DLM in its unique shape. The DLM group demonstrated a significantly smaller L/M ratio than the non-DLM group (DLM: 0.66±0.06, non-DLM: 0.74±0.05, p<0.001).

Conclusions: Reconstructed 3D images could help to demonstrate the whole morphology of DLM and reveal its unique features, in which DLM shows a significantly smaller L/M ratio as compared to non-DLM.

Categories: Pediatrics, Orthopedics, Anatomy

Keywords: the ratio of the medial to lateral anterior-to-posterior length (L/M ratio), anatomical feature, 3-dimensional image, magnetic resonance imaging, discoid lateral meniscus

Introduction

This article was previously presented as a poster at the ORS 2020 annual meeting on February 8, 2020.

The discoid lateral meniscus (DLM) represents a distinctive anatomical variation characterized by a larger and thicker lateral meniscus [1]. Incidence varies from 0.4% to 16.6%, being common disorder in Eastern Asian populations [2]. Its morphology, classified by Watanabe, includes incomplete, complete, or Wrisberg ligament types [3].

Magnetic resonance imaging (MRI) is a fundamental tool for diagnosing DLMs in clinical practice. Multiple quantitative MRI criteria have been proposed for DLM diagnosis. Silverman et al. [4] proposed that DLM is present if 3 or more, 5-mm-thick, contiguous sagittal images demonstrate continuity of the meniscus between the anterior and posterior horns. Araki et al. [5] reported that DLM is diagnosed if the transverse width at the mid-portions of the meniscal body exceeds 14 mm, independent of tibial width. Samoto et al. [6] presented that two parameters were useful in the diagnosis of the discoid meniscus: (1) Ratio of the meniscus to the tibia (RMT), the ratio of the minimum meniscal width to the maximum tibial width on the coronal slice, and (2) Percent coverage of the meniscus (PCM), which is the ratio of the sum of the width of the anterior and posterior horns to the meniscal diameter on the sagittal slice showing the maximum meniscal diameter.

The most accurate diagnostic thresholds were RMT > 20% or PCM > 75%. However, these criteria can be challenging to apply in cases of concomitant meniscal tears and displacement, as observed in tears, such as radial, longitudinal, and complex tears [7]. Treatment-wise, arthroscopic partial meniscectomy with or without repair is common, yet postoperative outcomes are often unsatisfactory [8, 9]. Interestingly, treated
DLMs can have worse prognoses than normal-shaped menisci [10], highlighting treatment challenges. Thus, to conduct an appropriate surgical treatment and to achieve a successful clinical outcome, it is desirable to evaluate the precise anatomy and pathology of the DLM in each patient.

While two-dimensional MRI images often fall short of capturing complete meniscal morphology, three-dimensional (3D) MRI has emerged for comprehensive quantification of meniscal volume and positioning. Notably, no study has explored DLM morphology using 3D MRI or evaluated its unique anatomical features. We posit that leveraging patient-specific 3D MRI represents a pivotal advance toward accurate anatomical assessment of DLM.

This study employs MRI to reconstruct patient-specific 3D DLM and non-DLM images via free software segmentation. The aim is to assess DLM 3D morphology and pinpoint its unique anatomical features.

**Materials And Methods**

**Participants**

This study was approved by the institutional review board (IRB ID# E-1228). Informed consent was obtained from all individual participants included in the study. The study population consisted of 31 consecutive knees with DLM and 45 consecutive knees without DLM as a control population, which was confirmed by arthroscopic surgeries conducted in our hospital, between 2017 and 2021. DLM was defined as RMT ≥ 0.20 in the coronal MRI image, as reported by Samoto et al., and was also confirmed by arthroscopy. In addition, cases that appeared to be DLM arthroscopically, belonged to the DLM group, even without an RMT > 0.20 on MRI. Furthermore, the DLM group was divided into subgroups according to the presence or absence of tears and the presence of complete or incomplete DLM. Complete DLM was defined as RMT > 0.32 as the cutoff value reported by Choi et al. [11]. The DLM group consisted of 20 males and 11 females aged 9-49 years (mean age, 24.2 years). A group of age-matched control patients without DLM, who underwent anterior cruciate ligament reconstruction or other surgeries (e.g., meniscectomy) at the same time, were included as a non-DLM group in this study. The non-DLM group comprised 22 males and 21 females aged 9-69 years (mean age, 28.5 years). Patients with previous meniscal surgery or those that could not be divided by software were excluded from the study population.

**MRI scanning protocol**

MRI examinations were performed using a 1.5-T MRI scanner with a dedicated knee coil (Achieva 1.5T; Philips Medical Systems, Netherlands) at a joint research facility. The knee was positioned at 15°flexion and 0°rotation. These knees were assessed using coronal T2-weighted spin-echo images (repetition time, 4243 ms; echo time, 70 ms), sagittal proton density-weighted spin-echo images (PDWI) (2137/10), and axial PDWI (2389/12). The section thickness was 3 mm for the axial, coronal, and sagittal views. In addition, 3D MRI scanning by PDWI (1500/28) was performed with 0.7 mm slice thickness and 0.35 mm interslice gap. Only the axial plane was scanned using this technique, and the total scanning time was 3 min 12 sec. The 3D reconstruction technology was used to obtain images at any level in the coronal and sagittal planes.

**MRI Data Segmentation, Processing, and Analysis**

MR images were pseudonymized and converted from DICOM (digital imaging and communications in medicine) to NIFTI (Neuroimaging Informatics Technology Initiative), cartilage of tibia plateau and menisci were then semi-automatically segmented using an active contour evolution algorithm implemented in the ITK-SNAP software (ITK-SNAP 3.8.0, http://itksnap.org). 3D surface images of the medial and lateral menisci were reconstructed, as described in a previous report, using the software [12].

The images of the menisci were segmented using the thresholding function with manual editing performed by a trained orthopedic surgeon. The 3D menisci and cartilage images were then generated and optimized by limited smoothing (Fig. 1).
FIGURE 1: The 3D menisci and cartilage images were generated using ITK-SNAP.

Multiple arbitrary points were plotted in the range of the meniscus (A), and the software automatically extracted the meniscus (B). Pressing the "update" button in the 3D display panel provided a 3D view (C).

Regarding the indices of meniscus size, two quantitative parameters that were reported by Samoto et al. [6], were measured using a 3D image on ITK-SNAP with a coordinate system (Fig. 2A). The two parameters were as follows: (1) Ratio of the meniscus to the tibia (RMT), the ratio of the minimum meniscal width to the maximum tibial width in the 3D image, and (2) Percent coverage of the meniscus (PCM), which is the ratio of the sum of the width of the anterior and posterior horns to the meniscal diameter in a sagittal 3D image (Fig. 2B). Based on the observation of the entire 3D image of the menisci, we added a novel index: (3) a ratio between the anterior-to-posterior diameter of the lateral meniscus and the anterior-to-posterior diameter of the medial meniscus (L/M ratio) (Fig. 2C). Two orthopedic surgeons (AN and MI) performed the measurements in a randomized order, twice by each rater, with at least a 30-day duration between the measurements. Observers selected the image of the articular surface of the tibial plateau viewed from above and calculated 3 parameters in planar coordinates using the ITK-SNAP software.

Statistical analysis

Patient demographic data were compared between the two groups using Pearson’s χ² test with Yate’s continuity correction, and 3 parameters (RMT, PCM, and L/M ratio) were compared between the two groups using the Mann-Whitney U test. These parameters were also statistically analyzed for subgroups with and without tears, and for subgroups with complete or incomplete DLM. The Mann-Whitney U test was applied for 2 subgroups comparisons. Intra- and inter-observer reliabilities were analyzed using intraclass correlation coefficients (ICCs). Statistical significance was defined as a 95% confidence interval (CI) for hazard ratios not including 1.0, and the alpha was set to 0.05.

FIGURE 2: Each parameter is measured using the 3D image on ITK-SNAP as the coordinate system.

A: The position was displayed in X-Y-Z coordinates in a 3D image.

B: The RMT and PCM were measured according to previous research when the 3D image was viewed from the top (middle). RMT = a/b, PCM = (c+d)/e

C: L/M ratio was calculated by dividing the anterior to posterior diameter of the lateral meniscus by that of the medial meniscus. L/M ratio = L/M

Results

There were no significant differences in age or sex between the two groups. In the DLM group, there were 10 cases of complete DLM and 21 cases of incomplete DLM, according to a previous report [11]. Furthermore, nine cases of DLM with tears were included in the DLM group (Table 1). Of the nine cases with tears, two had complete DLM, while the remaining cases had incomplete DLM.
### TABLE 1. Patient's Demographic Data

<table>
<thead>
<tr>
<th></th>
<th>non-DLM group (n=43)</th>
<th>DLM group (n=31)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>28.5 ± 15.3</td>
<td>24.2 ± 14.7</td>
<td>n.s.*</td>
</tr>
<tr>
<td>Sex: Men: Female</td>
<td>22:21</td>
<td>20:11</td>
<td>n.s.**</td>
</tr>
<tr>
<td>Morphology of DLM(n)</td>
<td>Complete / Incomplete</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Meniscus Tear (n)</td>
<td>(+) / (-)</td>
<td>none</td>
<td></td>
</tr>
</tbody>
</table>

*The Mann–Whitney U test, **Pearson's χ2 test with Yate's continuity correction

### TABLE 1: Patient's Demographic Data

The DLM group (n=31) showed a significantly larger RMT than the non-DLM group (n=43, DLM: 0.26±0.10; non-DLM: 0.10±0.04, p<0.001). With regard to PCM, the DLM group had a significantly larger value than the non-DLM group (DLM: 0.84±0.23; non-DLM: 0.50±0.10, p<0.001). The DLM group had a significantly smaller L/M ratio than the non-DLM group (DLM: 0.66±0.06; non-DLM: 0.74±0.05, p<0.001) (Table 2).

### TABLE 2. Values of each parameter in the non-DLM and DLM groups

<table>
<thead>
<tr>
<th></th>
<th>non-DLM group (n=43)</th>
<th>DLM group (n=31)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMT</td>
<td>0.10 ± 0.04</td>
<td>0.26 ± 0.10</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>PCM</td>
<td>0.50 ± 0.10</td>
<td>0.84 ± 0.23</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>L/M ratio</td>
<td>0.74 ± 0.05</td>
<td>0.66 ± 0.06</td>
<td>&lt;0.001*</td>
</tr>
</tbody>
</table>

RMT: Ratio of the meniscus to the tibia, PCM: Percent coverage of the meniscus *The Mann–Whitney U test

### TABLE 2: Values of each parameter in the non-DLM and DLM groups

Subgroup analysis between the complete and incomplete DLM groups showed no significant differences in PCM and L/M ratio (Table 3). In addition, subgroup analysis between the cases with and without tears in the DLM group was performed. It was demonstrated that RMT and PCM values were significantly smaller in cases with tears, and the torn DLM showed a significantly larger L/M ratio (Table 4).

### TABLE 3. Difference in values of morphological parameters between complete and incomplete DLM groups

<table>
<thead>
<tr>
<th></th>
<th>Complete DLM group (n=10)</th>
<th>Incomplete DLM group (n=21)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCM</td>
<td>0.97 ± 0.09</td>
<td>0.78 ± 0.24</td>
<td>n.s.</td>
</tr>
<tr>
<td>L/M ratio</td>
<td>0.65 ± 0.06</td>
<td>0.67 ± 0.07</td>
<td>n.s.</td>
</tr>
</tbody>
</table>

complete discoid: RMT > 0.32

### TABLE 3: Difference in values of morphological parameters between complete and incomplete DLM groups
### TABLE 4: The difference in values of morphological parameters associating with the presence of the tear in the DLM group

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tear+ (n=9)</th>
<th>Tear- (n=22)</th>
<th>P</th>
</tr>
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<tbody>
<tr>
<td>RMT</td>
<td>0.18 ± 0.12</td>
<td>0.28 ± 0.09</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>PCM</td>
<td>0.65 ± 0.22</td>
<td>0.91 ± 0.18</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>L/M ratio</td>
<td>0.74 ± 0.03</td>
<td>0.63 ± 0.05</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

The inter- and intra-observer ICC values were 0.923 (95% CI: 0.854-0.951) and 0.911 (95% CI: 0.848-0.947) for the L/M ratio.

### Discussion

In this study, we demonstrated the 3D imaging of the DLM with the segmentation of MR images from a common 1.5-T MRI scanner. In addition, to our knowledge, this is the first report revealing the unique feature of DLM, i.e., the L/M ratio in DLM patients is smaller than that in non-DLM patients.

DLM has been reported to be especially prevalent in Eastern Asia, including Japan and Korea [2]. Arthroscopy or MRI is considered the standard diagnostic procedure for DLM diagnosis. To date, for the diagnosis of DLM by MRI, the 2D sequence has been generally used; however, understanding 3D morphology is not easy with 2D MRI, in which information is lost by the slice thickness [13]. Especially, the morphology of torn DLM is difficult to interpret due to the limited information obtained from 2D MRI. Meanwhile, 3D sequence and high-resolution MRI have become widespread in recent years [14, 15]. They can reconstruct any cross-section and are promising techniques for evaluating various structures. Okazaki et al. [16] reported that a major benefit of 3D MRI is its ability to estimate the precise size and shape of the entire meniscus. Therefore, we speculated that the entire image of the meniscus could be captured by imaging it in a 3D sequence and creating a 3D image. There are several software programs for reconstructing 3D images with clear interfaces and intuitive segmentation tools [17]. The software we used in this study was user-friendly, had high-performance, and was freely available. Thus, it was useful for obtaining a 3D image in a semi-automatic manner.

Furthermore, arthroscopy has been widely used as a standard diagnostic procedure for DLM; however, even with arthroscopy, it has been difficult to obtain the entire configuration because of the limited views it offers. Dandy et al. [18] reported that the inverted-type DLM tear looks like a normal lateral meniscus without a meniscus tear, at first glance, and that probing is necessary to expose the inverted portion. Our approach has the potential to describe the whole meniscus in each patient, and an inverted-type DLM tear could be detected before the operation (Fig. 3). We believe that it is very useful to preoperatively detect not only the inverted posterior horn, but also the inverted anterior horn.
FIGURE 3: Case presentation

Left lateral meniscus injury in a 23-year-old male. We performed arthroscopic examination and partial meniscectomy, 2D and 3D views of the meniscus and intraoperative arthroscopic findings.

A: Coronal and sagittal knee slices. The characteristic wide image of the DLM could not be confirmed on the coronal slice. The continuous meniscus image in the front and rear could not be confirmed, even in the sagittal slice.

B: Arthroscopic view depicting the discoid lateral meniscus with a flap tear. (1) The flap was not evident in the lateral portal view. (2) The flap was unclear in the view of the medial portal. (3,4) The flap tear was pushed from the lower surface of the anterior horn with a probe and then reduced. (5) Morskite forceps were used for traction and resected using another portal. (6) At first glance, there was no change from (2), but the flap tear was resected.

C: It was easy to visualize the torn meniscus inverted forward in the 3D image.

3D sizing of the meniscus has been performed in meniscus implantation studies [19], and their data report a median anteroposterior diameter of 47.2 mm for the medial meniscus and a median anteroposterior diameter of 35.6–35.8 mm for the lateral meniscus. Pollard ME et al. [20], also studied 21 fresh frozen, above-knee amputation specimens with intact cruciate ligaments and menisci and reported the meniscus length. The medial meniscus length was 45.0 ± 3.8 mm, and the lateral meniscus length was 34.0 ± 5.2 mm. From these data, the calculated L/M ratios were 75.6% and 79.0%, respectively. These values were very close to the L/M ratio of our non-DLMs. This supports the unique anatomical features of the DLM depicted in the 3D image.

Few studies have addressed the anteroposterior diameter of the menisci. Choi et al. [11] reported that the insertion center of the posterior horn of the lateral meniscus is located more medially to the apex of the lateral tibial eminence in DLM than in non-DLM. A limitation of this study is that the insertion center of the posterior horn of the lateral meniscus was evaluated only on the coronal plane and not on the sagittal or axial planes. The anteroposterior diameter of the DLM must be reduced because the anterior and posterior positions of the roots are different from those of the non-DLM. Our study did not evaluate the reason for the lower L/M ratio in the patients with DLM. However, it is speculated that hypoplasia of the lateral compartment of the femur and tibia of DLM patients would lead to a smaller anteroposterior diameter of the tibia and lateral meniscus.

Although DLM has been described [1, 2, 21] as large and it widely covers the articular surface of the tibial plateau, our group reported for the first time that DLM has a smaller L/M ratio than non-DLM. The L/M ratio could potentially be recognized as one of the diagnostic parameters of DLM without being affected by body size. Notably, because the L/M ratio could be affected by tears in the DLM, we need to be careful in evaluating the morphology of the torn DLM. In other words, torn DLM has peripheral rim instability or a natural consequence of spreading due to abnormal tissue property [22].

These preoperative 3D images are helpful in unveiling unique features and designing an appropriate partial meniscectomy, although there is no clear answer for the optimal treatment of this entity. Hence, the approach described here is feasible in daily practice without any additional cost. We also believe that the accumulation of clinical images and knowledge will accelerate our understanding of this enigmatic disorder and improve clinical outcomes. In future, we plan to investigate the changes in the 3D morphology of the DLM between preoperative and postoperative conditions, after several treatments for this pathology.

This study has several limitations. First, the sample size was small. Second, in the DLM group, the presence of a tear significantly increased the L/M ratio; however, the inclusion of a tear case in the DLM group may be a limitation when comparing the DLM and non-DLM groups. Finally, the significance of the small L/M ratio in the DLM group compared with that in the non-DLM group was not investigated. In addition, the postoperative L/M ratio and clinical results were not investigated.

Despite several limitations, the 3D images obtained in this study were useful for describing the unique features of DLM as well as for interpretation of DLM, with the aid of previously established quantitative
methods. This study also reported that the L/M ratio in patients with DLM was smaller than that in patients without DLM.

Conclusions
The 3D images obtained in this study were useful for describing the unique features of DLM as well as for interpretation of DLM, with the aid of previously established quantitative methods. Reconstructed 3D images could help to demonstrate the whole morphology of DLM and reveal its unique features. This study also reported that the L/M ratio in patients with DLM was smaller than that in patients without DLM.

Additional Information
Disclosures
Human subjects: Consent was obtained or waived by all participants in this study. Ethical Committee for Clinical Research of Hiroshima University issued approval E-1228. This study was approved by the institutional review board (IRB ID# E-1228). Informed consent was obtained from all individual participants included in the study. Animal subjects: All authors have confirmed that this study did not involve animal subjects or tissue. Conflicts of interest: In compliance with the ICMJE uniform disclosure form, all authors declare the following: Payment/services info: All authors have declared that no financial support was received from any organization for the submitted work. Financial relationships: All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. Other relationships: All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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References

