Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 59 Issue: 03:2026
DOI: 10.5281/zenodo.19107659

RADIOLOGICAL VISUALIZATION AND ANALYSIS OF ANTEROLATERAL LIGAMENT: A CLINICAL IMAGING STUDY

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Abstract

Background: The anterolateral ligament (ALL) of the knee is an important secondary stabilizer against anterolateral rotatory instability. However, its depiction on conventional Magnetic Resonance Imaging (MRI) has been inconsistent, limiting its clinical utility. This study aimed to validate an optimized 3.0 Tesla (3.0T) MRI protocol for consistent visualization of the ALL, perform morphometric analysis, and assess its diagnostic reliability as an independent imaging technique. **Methods:** This cross-sectional, descriptive study analyzed 100 consecutive knee MRI examinations obtained using a 3.0Tesla Philips Achieva. The imaging protocol incorporated a high-resolution 3D Proton Density (PD) VISTA sequence with 0.7 mm isotropic voxels. Multiplanar reformation (MPR) was standardized to align with the ALL's anatomical axis. Each scan was evaluated for ligament visibility, morphology, and morphometric parameters including length, width, and thickness. Inter-observer reliability was calculated using the Intraclass Correlation Coefficient (ICC). **Results:** The optimized protocol achieved a 90.0% (90/100 knees) ALL identification rate, with 68.0% fully and 22.0% partially visualized. The PD-FS sequence provided the highest detection rate (92%). The tibial insertion was the most consistently visualized portion (95.0%). Morphometric assessment yielded reproducible values across observers. Inter-observer reliability was excellent for all parameters, with ICC values between 0.82 and 0.91 ($p < 0.001$). **Conclusion:** A standardized 3.0T MRI protocol employing high-resolution 3D sequences and MPR alignment offers reliable and reproducible assessment of the anterolateral ligament. This approach ensures consistent visualization and precise morphometric evaluation, supporting MRI as a dependable, non-invasive modality for integrating ALL assessment into the diagnostic evaluation of complex knee instability and enhancing preoperative planning.

Keywords: Anterolateral Ligament (ALL); Magnetic Resonance Imaging (MRI); Radiological Analysis; Multiplanar Reformation (MPR); Knee Instability.

Take-Home Message

- An optimized 3.0T MRI protocol with high-resolution 3D sequences can reliably visualize the anterolateral ligament (ALL) in 90% of cases.
- Multiplanar reformation (MPR) is essential for aligning the imaging plane with the ALL's oblique course, overcoming limitations of standard 2D imaging.

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- Proton density with fat saturation (PD-FS) sequences provide the best tissue contrast for identifying the ALL.
- MRI-based morphometric measurements of the ALL are highly reproducible between observers, supporting its use in clinical assessment.
- This validated protocol enhances diagnostic confidence and can improve preoperative planning for patients with suspected anterolateral rotatory instability.

1. INTRODUCTION

Anterior cruciate ligament (ACL) reconstruction remains a widely accepted and highly successful intervention within sports-related orthopedic practice. However, approximately one-fifth to one-third of individuals continue to have unsatisfactory outcomes, often attributed to ongoing anterolateral rotational instability. [1,2] The continued presence of a positive pivot-shift sign after ACL reconstruction indicates that additional anatomical structures contribute to rotational stability of the knee beyond the ACL itself. [3] Consequently, clinical focus has expanded beyond the ACL to include secondary extra-articular stabilizers.

This shift has renewed attention toward the anterolateral ligament (ALL), first described by Paul Segond in 1879.[4] Rediscovered through detailed anatomical studies, the ALL is now recognized as a distinct ligament, prompting extensive research into its biomechanical function. [5,6] Its function as a secondary stabilizer is confirmed by studies, especially in ACL-deficient knees where it restricts internal tibial rotation. [7,8]

Although substantial anatomical and biomechanical data support the clinical relevance of the ALL, reliably identifying its injuries through non-invasive imaging techniques continues to be difficult. While MRI is commonly used to assess soft-tissue structures around the knee, the ALL's orientation, small caliber, and close relationship to adjacent tissues make it difficult to visualize consistently. Visualization rates for the ALL on conventional two-dimensional MRI have been reported across an extremely broad range (22–100%), creating uncertainty regarding its true clinical visibility. [9,10]

Emerging improvements in MRI hardware and sequence technology have helped overcome several previous obstacles in imaging the ALL. The integration of high-field strength (3.0T) systems, thin-slice high-resolution 3D sequences, and standardized multiplanar reformation (MPR) techniques enables improved visualization by aligning the imaging plane with the ALL's anatomical axis and minimizing partial volume artifacts. Hecker et al.[11] demonstrated that this standardized approach achieved visualization in over 94% of cases, indicating that the prior "invisibility" of the ALL stemmed from methodological, not anatomical, limitations.

Before such imaging methods can enter routine practice, they must prove consistent and reproducible across different observers and institutions. A standardized protocol is essential to ensure consistent identification and accurate morphometric assessment across observers. Accordingly, this study was undertaken to validate an optimized 3.0T MRI protocol for detailed visualization and morphometric analysis of the ALL. The

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objectives were to determine its visualization rate, establish reproducible morphometric parameters, and evaluate inter-observer reliability—confirming its feasibility as a standalone diagnostic tool in clinical practice.

2. MATERIAL AND METHODS

2.1. Study Design and Ethical Approval

This work involved evaluating a series of knee MRI studies within a descriptive, cross-sectional imaging framework. The Sharda University Institutional Ethics Committee examined and approved the study protocol. All procedures complied with internationally accepted ethical standards for human research as outlined in the Declaration of Helsinki. Every participant in the prospective arm of the data collection gave their informed consent.

2.2. Participant Selection

This study includes 100 consecutive knee MRI exams conducted between January 2023 and December 2023. A targeted sampling approach was applied, selecting cases directly from the institution's PACS database.

2.2.1. Inclusion and Exclusion Criteria

Individuals over 25 with a clinically stable knee or those undergoing imaging for problems unrelated to the lateral compartment met the inclusion criteria for the MRI exams. To ensure the analysis focused on native, uninjured anatomy, scans were required to demonstrate a normal lateral compartment. Cases displaying any lateral compartment pathology—such as prior surgery, ligamentous tears, capsular injury, or substantial degenerative change—were excluded from assessment.

2.3. MRI Acquisition and Analysis

2.3.1. MRI Acquisition Protocol

A 3.0 Tesla Philips Achieva system, which uses a structural digital broadband architecture to provide a high signal-to-noise ratio (SNR) and spatial resolution, was used for all MRI exams. A 16-channel dedicated knee coil was used for all scans. For a broad anatomical survey, the imaging procedure comprised standard 2D sequences (T1-weighted and T2-weighted fat-saturated) with a 3 mm slice thickness. The primary dataset for analysis was obtained using a three-dimensional proton-density VISTA sequence configured with isotropic voxel dimensions of 0.7 mm. This order is ideal for producing multiplanar reformations of superior quality.[11,12]

2.3.2. Image Analysis

Image interpretation was performed independently by two experienced musculoskeletal radiologists who were masked to one another's assessments to prevent bias. A Philips IntelliSpace Portal workstation was used in accordance with a standardized assessment protocol:

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1. Initial Review: Standard 2D sequences were first examined to confirm that each scan met the inclusion and exclusion criteria.

2. Multiplanar Reformation (MPR): The high-resolution 3D PD VISTA datasets were processed using the two-step MPR method described by Hecker et al.[11] Initially, the viewing plane was positioned in the axial plane at a neutral rotation. The complete ligament was then seen on a single oblique coronal picture when the plane was obliquely rotated, pivoting on the ALL's femoral origin.

3. Radiological Assessment: On the optimized oblique coronal view, the ALL was evaluated for the following characteristics:

- **Visibility**: Ligament visualization was classified into three categories: complete, partial, or absent.
- **Morphology:** Classified as either cord-like (a distinct, narrow band) or band-like (a broader, flatter structure).
- **Morphometric Measurements:** Using calibrated PACS digital calipers, the following measurements were taken: ligament length (from femoral origin to tibial insertion), width (at the femoral origin, mid-substance, and tibial insertion), and thickness (at the mid-substance).
- **Anatomical Relationships:** The ALL's connection to the lateral meniscus and its attachment sites relative to bony landmarks (lateral epicondyle, Gerdy's tubercle, fibular head) were documented.

2.4. Statistical Analysis

IBM SPSS Statistics v28.0 was used to compile and analyze all the data. Basic morphometric and demographic parameters were summarized using descriptive statistical measures, including means, standard deviations, and percentages. Visibility rates were calculated with 95% confidence intervals. Agreement between observers was calculated using the Intraclass Correlation Coefficient for quantitative variables and Cohen’s Kappa for categorical assessments. Excellent agreement was defined as an ICC value greater than 0.80. For every analysis, a p-value of less than 0.05 was deemed statistically significant.

3. RESULTS

3.1. Visibility Rates and Sequence Efficacy

A total ALL identification rate of 90.0% (90/100 knees) was obtained in the analysis of 100 knee MRI exams using the standardized MPR technique applied to the thin-slice 3D datasets. Of these, the ligament was fully visualized as a continuous structure in 68.0% of cases and partially visualized in 22.0%. In only 10.0% of cases was the ALL classified as not visualized. This represented a significant improvement in visualization compared to reviewing standard orthogonal planes alone ($p < 0.001$) as shown in (Fig1).

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Among the sequences assessed, proton-density imaging with fat suppression provided the clearest contrast for delineating the ligament. This was found to be significantly superior to T1-weighted (78%) and T2-weighted (82%) sequences ($\chi^2 = 8.34$, $p = 0.003$). The tibial insertion was the most consistently identified component of the ligament (95.0% identification rate), followed by the femoral origin (90.0%) and the meniscal attachment (83.0%), as detailed in (Table 1) and shown in (Fig 2).

Fig 1: Representative MRI images of the knee from the study cohort, demonstrating various planes used for the radiological analysis of the anterolateral ligament

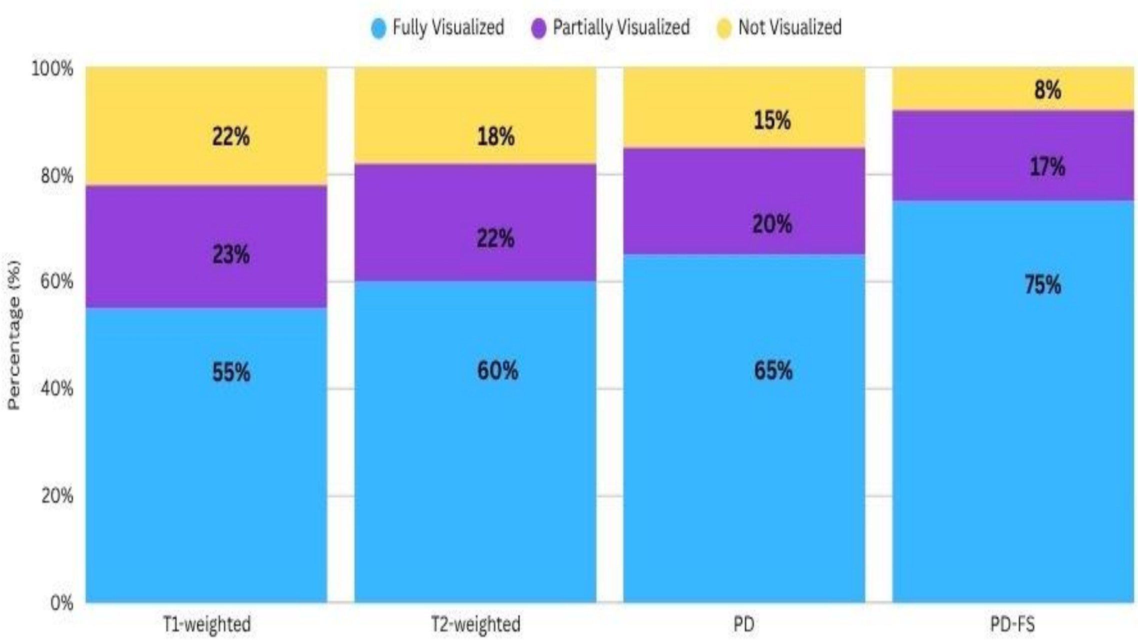

Fig 2: ALL identification rates on MRI by sequence type (n=100). The chart illustrates the superior performance of Proton Density with Fat Saturation (PD-FS) sequences for visualizing the ALL compared to T1, T2, and standard PD sequences

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Table 1: MRI Visibility of Anterolateral Ligament Components (n=100)

Component	Fully Visible (%)	Partially Visible (%)	Not Visible (%)	Total Identification Rate (%)
Femoral Origin	72 (72.0)	18 (18.0)	10 (10.0)	90.0
Meniscal Attachment	58 (58.0)	25 (25.0)	17 (17.0)	83.0
Tibial Insertion	85 (85.0)	10 (10.0)	5 (5.0)	95.0
Overall Ligament (Continuous)	**68 (68.0)**	**22 (22.0)**	**10 (10.0)**	**90.0**

3.2. Morphometric Analysis and Inter-Observer Reliability

Morphometric measurements were successfully obtained from the 68 knees in which the ALL was fully visualized. The ALL's average length was 34.1 ± 3.2 mm. The mean widths showed a distinctive broadening at its endpoints, measuring 5.6 ± 1.0 mm at the femoral origin, 4.9 ± 0.8 mm at the mid-substance, and 7.1 ± 1.3 mm at the tibial insertion. The mean thickness at the mid-substance was 1.2 ± 0.3 mm. These measurements are summarized in (Table 2).

The inter-observer reliability for all morphometric measurements was excellent. For measurements of length (ICC = 0.87), femoral width (ICC = 0.82), mid-substance width (ICC = 0.85), and tibial width (ICC = 0.91), the Intraclass Correlation Coefficient (ICC) showed good agreement between the two radiologists. All ICC values were statistically significant ($p < 0.001$), confirming the high reproducibility of the measurement protocol (Table 2).

Table 2: MRI-Based Morphometric Measurements and Inter-Observer Reliability (n=68)

Parameter	Mean ± SD (mm)	Inter-Observer ICC (95% CI)	p-value
Length	34.1 ± 3.2	0.87 (0.78 - 0.93)	<0.001
Femoral Width	5.6 ± 1.0	0.82 (0.71 - 0.89)	<0.001
Mid-substance Width	4.9 ± 0.8	0.85 (0.75 - 0.91)	<0.001
Tibial Width	7.1 ± 1.3	0.91 (0.85 - 0.95)	<0.001
Mid-substance Thickness	1.2 ± 0.3	0.84 (0.73 - 0.90)	<0.001

4. DISCUSSION

The findings support the use of an optimized 3.0-Tesla MRI protocol as a consistent and dependable tool for non-invasively examining the ALL. Our findings demonstrate that with appropriate imaging techniques, MRI can serve as a robust standalone tool for identifying and measuring the ALL, a crucial step toward its routine integration into the diagnostic workup of complex knee instability.

4.1. Establishing MRI as a Valid and Reliable Diagnostic Tool

The principal contribution of this study lies in establishing a highly dependable MRI protocol for ALL evaluation. Using a standardized MPR technique, a 90% identification rate was achieved—significantly surpassing the inconsistent visualization reported in earlier studies employing 1.5T magnets and conventional 2D sequences.[9,10]

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Our findings strongly support Hecker et al., who demonstrated that the historical "invisibility" of the ALL was largely due to methodological limitations.[11] By aligning the imaging plane with the ligament's oblique orientation, partial volume averaging is minimized, enabling consistent visualization from origin to insertion. These results demonstrate that such advanced imaging strategies are practical and effective for routine clinical assessment.

Furthermore, the protocol's reproducibility is confirmed by its outstanding inter-observer reliability, which has ICC values between 0.82 and 0.91. When standardized techniques are applied, this agreement validates the objectivity and consistency of morphometric measurements. This dependability boosts radiologists' confidence and makes multicenter research, long-term evaluations, and clinical implementation easier. Thus, quantitative assessment of ligament dimensions offers a more reliable indicator of integrity than simple qualitative inspection.

4.2. Optimizing the Imaging Protocol for Clinical Practice

This study presents practical, evidence-based recommendations for optimizing imaging protocols to enhance ALL visualization. The marked superiority of PD-FS sequences, demonstrating a 92% detection rate, corresponds with consensus statements from organizations such as the International ALC Consensus Group.[12] Fat-suppressed sequences enhance visualization by increasing contrast between the ligament's low-signal collagen fibers and surrounding higher-signal soft tissues.

The tibial insertion emerged as the most consistently visualized component (95% detection), serving as a dependable anatomical landmark for tracing the ligament's course. This aligns with its broad, fan-shaped attachment and close relation to the Segond fracture site, making it a crucial reference in knee imaging. [4] Furthermore, the study underscores the indispensable value of multiplanar reconstruction (MPR).

The findings confirm that conventional orthogonal planes inadequately depict the obliquely oriented ALL. Incorporating MPR into high-resolution 3D imaging should thus be standard in knee MRI protocols when anterior lateral rotational instability (ALRI) is suspected. This transition establishes MPR as an essential diagnostic practice rather than a purely academic tool.

4.3. Clinical Ramifications and Future Directions

Precise identification of ALL pathology before surgery can significantly influence clinical management and outcomes. Up to 79% of knees with ACL injuries had concurrent ALL abnormalities, which are linked to increased rates of ACL graft failure and permanent high-grade pivot shifts.[13] A validated MRI protocol enables surgeons to identify patients with combined ACL and ALL injuries who are most likely to benefit from a combined intra- and extra-articular reconstruction.[14,15] Objective imaging-based measurements offer a more individualized basis for planning interventions compared with solely relying on subjective clinical tests.

These findings hold relevance for the North Indian population, from which our cohort was derived, offering population-specific radiological insights. Despite strong results, the study has limitations. It was conducted at a single institution, necessitating validation in larger, multicenter cohorts. Moreover, imaging data were not correlated with surgical or clinical outcomes. Further prospective studies linking imaging findings to surgical results and long-term outcomes are required to strengthen these observations. [16, 17] The establishment of conclusive indications and advantages of combined ALL reconstruction depends on these studies, which are based on a standardized imaging framework. [18, 20]

5. CONCLUSION

The results of this work demonstrate that a refined 3.0-Tesla MRI technique, which utilizes high-resolution three-dimensional imaging and multiplanar reconstruction, can consistently and accurately evaluate the anterolateral ligament without requiring invasive procedures. We have established that this protocol allows for consistent visualization of the ALL and enables morphometric measurements with high inter-observer agreement. The outcomes of this study help address an important limitation in current diagnostic practices by offering clinicians a proven imaging approach that enhances preoperative decision-making and supports more individualized management for patients experiencing complex knee instability. This study is aligned with UN Sustainable Development Goal No.3 (Good Health and Well-being).

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