Standard MRI May Not Predict Specific Acute Anterior Cruciate Ligament Rupture Characteristics

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Background: There has been renewed interest in the concept of anterior cruciate ligament (ACL) suture repair (ACLSR). Morphologic characteristics of the ruptured ACL remnant play a role in deciding whether a patient is eligible for ACLSR. However, no classification of these characteristics of ACL rupture on magnetic resonance imaging (MRI) scans has yet been compared with intraoperative findings in the context of ACLSR.

Purpose: To investigate the value of using preoperative MRI to predict specific characteristics of acute complete ACL rupture.

Study Design: Cohort study (diagnostic); Level of evidence, 2.

Methods: A total of 25 patients were included. Two radiologists classified ACL rupture location and pattern on preoperative 1.5-T MRI scans with a standard sequence; the results were compared with the corresponding findings at arthroscopy conducted by a single surgeon. The agreement between the MRI and surgical findings was calculated using Cohen $k$ values. Furthermore, the reliability coefficients of the MRI classifications within and between radiologists were calculated.

Results: The agreement between MRI classification and arthroscopic findings for ACL rupture location was slight (Cohen $k$, 0.016 [radiologist 1] and 0.087 [radiologist 2]), and for ACL rupture pattern, this was poor to slight (Cohen $k$, $<0$ and 0.074). The intraobserver reliability of MRI classification for ACL rupture location was moderate for radiologist 1 and slight for radiologist 2 (Cohen $k$, 0.526 and 0.061, respectively), and for ACL rupture pattern, this was slight for radiologist 1 and 2 (Cohen $k$, 0.051 and 0.093, respectively). The interobserver reliability of MRI classification for ACL rupture location and pattern was slight between radiologists (Cohen $k$, 0.172 and 0.040, respectively).

Conclusion: In the current study, we found poor to slight agreement between MRI classification and arthroscopic findings of specific ACL rupture characteristics. In addition, the intra- and interobserver reliability for MRI classification of the ACL rupture characteristics was slight to moderate.

Keywords: ACL; biologic healing enhancement; biology of ligament; ACL reconstruction; ACL suture repair; dynamic intraligamentary stabilization; MRI
ACL rupture can be performed at a later time, after the criteria for recovery of knee function have been met.\textsuperscript{8,10,15-17,35}

Preoperative assessment of these characteristics of ACL rupture using magnetic resonance imaging (MRI) may be useful in the decision making regarding ACLSR for complete ACL rupture. In general, the value of using MRI to diagnose partial or complete ACL tears as well as to locate a partial ACL tear in the anteromedial or posterolateral bundle has been established, and MRI findings have been compared with those at the time of surgery.\textsuperscript{5,23} However, there is paucity of literature comparing preoperative MRI findings and surgical findings regarding specific characteristics of complete ACL rupture that are relevant to ACLSR (ie, ACL rupture location, ACL rupture pattern, and disruption of the synovial sheath).\textsuperscript{18,31}

In a 2019 randomized controlled trial (RCT), Hoogeslag et al\textsuperscript{9} reported no inferiority for dynamic augmented ACLSR as compared with ACLR in terms of subjective patient-reported outcomes. In all patients, characteristics of acute complete ACL rupture were classified at the time of surgery.\textsuperscript{8,9} However, these were not yet compared with the characteristics of ACL rupture on the corresponding preoperative MRI scans. Therefore, the purpose of this study was to investigate the value of using preoperative MRI to predict morphologic characteristics of acute complete ACL rupture in patients who participated in the RCT. Our hypotheses were that (1) MRI would be accurate for classifying specific characteristics of ACL rupture as compared with findings at time of surgery and (2) classification of specific characteristics of ACL rupture on MRI scans would be reliable within and between radiologists.

METHODS

Patients

This cohort study compared characteristics of ACL rupture classified at the time of surgery with those classified on preoperative MRI scans. Patients were selected from the 2019 RCT of Hoogeslag et al.\textsuperscript{9} In the RCT, during the study period of January 2015 to March 2016, a total of 48 patients with acute complete ACL rupture were randomized to undergo either dynamic augmented ACLSR within 3 weeks after injury (n = 24) or ACLR after meeting criteria for recovery of knee function (n = 24).\textsuperscript{9,16,17} In addition, 3 patients underwent dynamic augmented ACLSR before the RCT to reduce the learning curve effect of the surgical technique during the study. See Hoogeslag et al\textsuperscript{9} for the RCT procedures and outcomes.

All 27 patients who underwent ACLSR had surgery within 3 weeks after injury, with a median 14 days (interquartile range [IQR], 12-17). In contrast, all 24 patients who underwent ACLR had surgery >3 weeks after injury, with a median 47 days (IQR, 42-71). Given that morphologic changes of ruptured ACL remnants are known to occur as soon as 3 weeks after injury and this could interfere with the comparability of MRI findings versus those at the time of surgery, only patients who underwent ACLSR (n = 27) were included in the present study.\textsuperscript{5,9} Patients included in the RCT who underwent MRI of the injured knee elsewhere were excluded from the present study.

ACL Rupture Classification at the Time of Surgery

All surgical procedures started with standard arthroscopy of the knee, with joint lavage for hemarthrosis. Afterward, ACL rupture characteristics were classified by location (proximal, middle, or distal third), pattern (not lacerated or lacerated into 2 parts or >2 parts), and integrity of the synovial sheath (completely, ≥50%, or <50% intact), as described by Henle et al\textsuperscript{9} (Figure 1).

The described characteristics of ACL rupture were assessed by visual inspection, probing of the ligament remnants, and tensioning of the ligament remnants using a grasper. One surgeon (R.A.G.H.) with considerable experience in ACL surgery performed all the surgical procedures and ACL rupture classifications, and the findings were documented in an operative report form. The surgeon was not blinded to the preoperative MRI scans during the surgical procedure. However, classification of specific characteristics of ACL rupture on MRI scans was performed at a later time, in the context of the present study; as such, this did not influence classification at the time of surgery.

MRI Scan and ACL Rupture Classification

All MRI of the included patients was performed using a 1.5-T MRI scanner (MAGNETOM Avanto fit; Siemens) according to a standardized protocol for the knee (Table 1). All examinations were performed with the patients in the supine position and their knees in extension and without sedation or anesthesia. The knee was supported by a pillow and secured by an extremity coil (Tx/Rx 15-Channel Knee Coil; Siemens).

All MRI scans were assessed using JiveX DICOM Viewer software (Visus Technology). The same classification system that was used during assessment at the time of surgery was used for MRI assessment of the ACL rupture characteristics (Figure 2).\textsuperscript{9} To determine the ACL rupture location on the MRI scan, first the central point of the femoral ACL attachment was determined in the transverse plane, which was then correlated with the sagittal and coronal planes using a localizer. The same procedure was followed to determine the center of the ACL attachment on the tibia. Finally, the distance between these points was measured and divided into 3 equal parts, representing the proximal, middle, and distal thirds of the native ACL, and the assessed ACL rupture location was accordingly classified. The ACL rupture pattern was classified on the basis of the severity of the laceration seen, using all scan directions. The integrity of the synovial sheath was not radiologically classified, as this is assessable only via MRI using specific sequences and/or contrast and these data were not available.\textsuperscript{11} The radiologists were blinded to the surgical findings.
Data Collection

Baseline characteristics of the included patients including sex, side of injury, body mass index, age at the time of knee injury, time from injury to surgery, time from injury to the MRI scan, and time from the MRI scan to surgery were recorded. Two experienced musculoskeletal radiologists (S.M.v.R. and R.P.H.D.) separately performed the described MRI classification on 2 occasions 12 weeks apart, and their findings were documented and tabulated. The documented classifications of the ACL rupture characteristics at the time of surgery of the included patients were retrieved from the operative report form and tabulated.

Figure 1. Classification of complete anterior cruciate ligament rupture characteristics at the time of surgery based on the rupture location, the rupture pattern, and the integrity of the synovial sheath. Image from Henle et al. Reproduced with permission from BMC/Springer Nature.
For classification of ACL rupture location and pattern, the agreement between MRI scans and surgery was calculated using the single-measure 2-way absolute agreement intraclass correlation coefficient (Figure 3).\textsuperscript{14} Furthermore, to calculate the intra- and interobserver reliability of MRI findings within and between radiologists, the same procedure was followed. The resulting Cohen \( \kappa \) values were interpreted as poor (<0.00), slight (0.00-0.20), fair (0.21-0.40),
Agreement Between MRI and Surgical Findings

Table 3 presents the agreement between the MRI classifications and the arthroscopic findings for ACL rupture location and pattern. The agreement for ACL rupture location was slight (Cohen $\kappa$, 0.016 [radiologist 1] and 0.087 [radiologist 2]), and the agreement for ACL rupture pattern was poor to slight (Cohen $\kappa$, <0 and 0.074, respectively).

Intra- and Interobserver Reliability for MRI Classification of ACL Rupture Characteristics

Table 4 presents the intra- and interobserver reliability for MRI classification of ACL rupture location and pattern by radiologists 1 and 2.

TABLE 2
Baseline Characteristics

| Characteristic | Patients (N = 25) |
|---------------|-----------------|
| Sex           |                 |
| Male          | 21 (84)         |
| Female        | 4 (16)          |
| Age, y        | 21 (17-31)      |
| Side of injury|                 |
| Left          | 10 (40)         |
| Right         | 15 (60)         |
| Body mass index| 23.1 (21.4-24.5) |
| Time from, d  |                 |
| Injury to repair| 14 (12-16.5)    |
| Injury to MRI scan| 5 (1-14)       |
| MRI scan to repair| 8 (5-10)       |

$^a$As the data were not normally distributed, they are expressed as a median (interquartile range) or frequency (percentage). MRI, magnetic resonance imaging.

TABLE 3
Agreement Between MRI Classification (Radiologists 1 and 2) and Surgical Findings of ACL Rupture Location and Pattern

| Cohen $\kappa$ |
|----------------|
| Rupture Location | Rupture Pattern |
| Surgeon vs radiologist 1 (n = 50) | 0.016 | -0.012 |
| Surgeon vs radiologist 2 (n = 50) | 0.087 | 0.074 |

$^a$ACL, anterior cruciate ligament; MRI, magnetic resonance imaging.

TABLE 4
Intra- and Interobserver Reliability for MRI Classification of ACL Rupture Characteristics

| Cohen $\kappa$ |
|----------------|
| Rupture Location | Rupture Pattern |
| Intraobserver reliability, measurement 1 vs 2 |                 |
| Radiologist 1 (n = 25) | 0.526 | 0.051 |
| Radiologist 2 (n = 25) | 0.061 | 0.093 |
| Interobserver reliability |                 |
| Radiologist 1 vs radiologist 2 (n = 50) | 0.172 | 0.040 |

$^a$ACL, anterior cruciate ligament; MRI, magnetic resonance imaging.
the 2 radiologists. The intraobserver reliability for the ACL rupture location was moderate for radiologist 1 and slight for radiologist 2 (Cohen κ, 0.526 and 0.061, respectively). The intraobserver reliability for the ACL rupture pattern was slight for radiologists 1 and 2 (Cohen κ, 0.051 and 0.093, respectively). Furthermore, the interobserver reliability for the ACL rupture location and pattern was slight between the radiologists (Cohen κ, 0.172 and 0.040, respectively).

DISCUSSION

The most important finding of the present study is that the agreement was poor to slight between the MRI classification of ACL rupture characteristics and the findings at the time of surgery. In addition, intra- and interobserver reliability was slight to moderate for MRI classification of ACL rupture characteristics by the radiologists.

In general, MRI has been established as a valuable diagnostic tool for the evaluation of ACL injuries. However, studies investigating this have focused on the presence of a complete or partial ACL rupture and not on the presence of the characteristics of acute complete ACL rupture that were investigated in the present study. Additionally, although MRI findings to diagnose ACL rupture and to differentiate between the anteromedial and posterolateral bundle in a partial ACL tear have been compared with those at surgery, no MRI findings on characteristics of complete ACL rupture relevant to ACLSR have been compared with those at surgery.

First, 2 of 3 observers were already familiar with the radiologists for MRI assessment of ACL rupture characteristics, which provides more differentiation of the ACL rupture location in the proximal half as compared with the classification system applied in the present study. As the majority of the ACL ruptures are located in the proximal half of the ACL, this might have favored the results of van der List et al. Nevertheless, van der List et al. reported higher reliability coefficients for the classification of the ACL rupture location in a sample comparable with that of the present study (30 patients) with acute ACL rupture; the reliability coefficient for classification of the ACL rupture pattern, which was slight in the present study, was not analyzed.

This difference could be attributed to several reasons. First, 2 of 3 observers were already familiar with the radiologic classification system. The third observer was a radiologist who was new to the classification system, like the observers in the present study, and had a lower intraobserver reliability score than did the other 2 observers. This implies that familiarity with the classification system might improve the results.

Second, a different classification system was applied (modified Sherman), which provides more differentiation of the ACL rupture location in the proximal half as compared with the classification system applied in the present study. As the majority of the ACL ruptures are located in the proximal half of the ACL, this might have favored the results of van der List et al.

Third, despite being sufficient in both studies, the time between the first and second MRI assessments was 3 weeks, as opposed to 12 weeks in the present study, thereby reducing the risk of recall bias among the radiologists.

Fourth, reliability coefficients were calculated for 30 patients randomly selected from a larger group of 353 patients, who were scanned using 1.5- or 3.0-T MRI (not specified for this subgroup), as compared with 1.5 T in the present study. However, field strength alone does not necessarily result in better resolution of the MRI scan. Having a smaller slice thickness (3.0 vs 3.5 mm) which increases the signal-to-noise ratio, having a small gap (0.3 mm vs no gap) which decreases interference between adjacent slices, and using a dedicated knee coil with a larger number of receiver channels (15 vs 8 channels) would have resulted in better spatial resolution in the present study. Nevertheless, van der List et al. reported reliability coefficients for MRI assessment of ACL rupture location that were substantially higher than the values in the present study.

There have been some reports of excellent outcomes with augmented ACLSR for midsubstance ACL rupture with the addition of a bridging collagen scaffold, which might, at least in part, eliminate the decision making between ACLSR and ACLR on the basis of specific ACL rupture characteristics in the future. However, it seems that for now the final assessment of a patient’s eligibility for ACLSR should be made at the time of surgery.

Nevertheless, the value of using MRI in the classification of specific characteristics of acute complete ACL rupture might be improved in several ways as compared with the 1.5-T MRI with a standard sequence that was used in the present study. Although the capabilities of 1.5- and 3.0-T MRI scanners are not significantly different in the
diagnosis of ACL rupture in general, higher field strength improves the signal-to-noise and contrast-to-noise ratios.\textsuperscript{23} Higher field strength together with a small field of view and a dedicated knee coil with a larger number of receiver channels can optimize the spatial resolution, which may allow better visibility of the ACL rupture characteristics.\textsuperscript{24} Additional oblique scans in the coronal and axial planes improve visualization of the ACL, and a 3-dimensional MRI sequence might provide more information on the ACL rupture characteristics.\textsuperscript{1,12,20,22,25,26} Furthermore, it has been reported that MRI performed with the knee in flexion instead of extension improves accuracy in the diagnosis of partial and complete ACL ruptures in general. Although not investigated, this might improve the accuracy of MRI for classifying the characteristics of complete ACL rupture that were investigated in the present study.\textsuperscript{18}

This study has some limitations that need to be addressed. First, only 1 observer assessed the classification of the ACL rupture characteristics at the time of surgery. However, in ACLR procedures, it is common practice that decisions at the time of surgery are made by just 1 orthopaedic surgeon. In addition, assessments are based not only on the arthroscopic image but also on probing the ruptured ACL remnants at the time of surgery. Although arthroscopic images were available for all the included patients, probing could not be replicated by assessing only arthroscopic images. As such, the single-surgeon classification of ACL rupture characteristics at the time of surgery can be considered the current gold standard.

Second, although this study included a relatively small sample size, it was large enough to reject the null hypothesis. Additionally, while important for the decision making in surgical timing and technique, there is a paucity of studies concerning the investigated topic. This study is the first to validate specific rupture characteristics of acute complete ACL rupture on preoperative MRI scans against findings at the time of surgery in the context of ACLSR.

Third, the distribution of the ACL rupture characteristics in the present study differed from that reported by Henle et al,\textsuperscript{8} who had a much larger sample size (278 patients), and might not represent the normal distribution of the ACL rupture characteristics in the general population. In the present study, the reported frequency of a multilacerated ACL rupture pattern was higher than that reported by Henle et al. This further obscures the assessment of the ACL rupture characteristics and might have negatively affected the current results.

Fourth, the morphology of ruptured ACL remnants is known to change over time. Although MRI and surgery were not performed on the same day, the median time between MRI and surgery was 8 days (IQR, 5-10; range, 1-15). Thus, no relevant morphologic changes were expected between MRI and surgery. Furthermore, as the median time between injury and surgery was 14 days (IQR, 12-16.5; range, 9-20) and morphologic changes were reported to occur from 3 weeks on after injury, no major morphologic changes in the ACL remnants between MRI and surgery were expected from this perspective.

CONCLUSION

In the current study, we found poor to slight agreement between MRI classification and arthroscopic findings of specific ACL rupture characteristics. In addition, the intra- and interobserver reliability for MRI classification of the ACL rupture characteristics was slight to moderate.

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