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Original Research Article

Diffusion Weighted MRI in Evaluation of Traumatic Anterior Cruciate Ligament Lesions and Associated Injuries of the Knee Joint

Article History:

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Abstract: **Background:** Diffusion weighted imaging (DWI) has been used to diagnose ischemic stroke and to characterize neoplastic tissue. **Objective:** To assess the value of adding DWI to conventional magnetic resonance imaging (MRI) in traumatic anterior cruciate ligament (ACL) tears and associated knee injuries.**Methods:** This prospective study was carried out on 30 patients with clinically suspected ACL injuries after a history of knee trauma with or without other soft tissue knee injuries with no age predilection. Patients were classified according to their injuries by DWI into main injury including ACL tears partial in (n=19) and complete (n=9) and associated injuries such as meniscal tear (n=6), bone marrow contusion (n=4), medial collateral ligament injury grade 1 (n=5) and grade 2 (n=2). Nine patients underwent arthroscopy, the other patients were followed up clinically and after receiving medical treatment and physiotherapy.**Results:** The apparent diffusion coefficient value was significantly higher in bone marrow edema than in normal bone marrow. The diagnostic accuracy of conventional MRI and DWI for ACL tears concerning the arthroscopy diagnosis. The conventional MRI showed 67% sensitivity and 50% positive predictive value while specificity and negative predictive value were not calculated because the 3 cases that were categorized by arthroscopy as partial tear were seen as sprains by the conventional MRI. On the other hand, DWI showed 100% sensitivity, specificity, positive and negative predictive values.**Conclusions:** Adding DWI to conventional MRI sequences in differentiation between complete and partial ACL tears improves diagnostic performance.

Keywords: Anterior Cruciate Ligament, Diffusion Weighted Imaging, Knee Joint, Magnetic Resonance Imaging, Lesions

INTRODUCTION

Knee is the largest and one of the most important joints in the human body. Soft tissue knee injuries are common and very important to diagnose and treat well. Neglected knee injuries can affect quality of life and misdiagnosis can lead to inappropriate treatment and later risk for early development of knee osteoarthritis (OA) and disability [1, 2].

Anterior cruciate ligament (ACL) lesions can occur

during abduction and hyperextension with external rotation and direct forward displacement of the tibia, or internal rotation with the knee in full extension [3]. Diagnosis of ACL injuries depends on the combined results obtained from a physical examination and other diagnostic tools such as plain radiography, ultrasound, magnetic resonance imaging (MRI) and arthroscopy. On plain radiography ligament injury may be found indirectly through detection of associated fractures like avulsion of the ACL within the inter condylar eminence on lateral or tunnel view. Musculoskeletal ultrasound is an vital imaging diagnostic approach in diagnosis of ACL injuries as it is a non-invasive, low-cost procedure, but it is operator dependent [4, 5].

MRI of the knee joint is routinely performed for the diagnosis of ACL injuries. However, in some cases, differentiation between complete and incomplete tears is difficult because the ligament fibers may be obscured by edema. Ligament fibers have been shown to be better visualized on apparent diffusion coefficient (ADC) mapping because precise diagnosis of incomplete tears is substantial to provide non-operative management in patients [6].

The single shot echo planar imaging (SS-EPI) technique is the most used sequence in diffusion-weighted imaging (DWI), providing not only rapid image acquisition but reduced motion artifacts. It is a non-invasive method which measures the Brownian motion of water in its microscopic environment [7].

A hyperintense signal on DWI corresponds to an area where water motion is restricted and is not able to move out of the image plane. Because extracellular fluid motion is less restricted in comparison to intracellular fluid motion, more extracellular fluid will result in decreased signal. In contrast, high signal correlates to increased cellularity of the tissue because intracellular fluid motion is impeded by organelles [8].

The ADC of epiphyseal bone marrow in the knee is different in yellow bone marrow, red bone marrow, and traumatic bone marrow lesions (BML).Moreover, intact bone marrow demonstrates directional diffusion, whereas BML exhibits isotropic diffusion which proposes that the osseous trabeculae impose a physiological diffusion barrier [9].

This work aimed to assess the value of adding DWI to conventional MRI in traumatic ACL tears and associated knee injuries.

Methods:

This prospective study was carried out on 30 patients with clinically suspected ACL injuries after history of knee trauma with or without other soft tissue knee injuries with no age predilection.

The study was done from July 2021 to September 2024 after approval from the Ethical Committee Tanta University Hospitals, Tanta, Egypt. Approval Code: (34676/5/21). An informed written consent was obtained from the patients or relatives of the patient.

Exclusion criteria were patients with general contraindications for MRI study as patients with ferromagnetic implants, pacemakers, cochlear implants and aneurysmal clips, non-traumatic ACL injuries and claustrophobic patients.

Patients were classified according to their injuries by DWI into main injury including ACL tears partial in (n=19) and complete (n=9) and associated injuries such as meniscal tear (n=6), bone marrow contusion (n=4) and medial collateral ligament (MCL) injury grade 1 (n=5) and grade 2 (n=2). Nine patients underwent arthroscopy, the other patients were followed up clinically and after receiving medical treatment and physiotherapy.

All patients were subjected to complete history taking, clinical examination and radiological investigation [MRI of knee with conventional and diffusion MRI sequences using a closed MRI machine].

Image acquisition:

Patients were examined in supine position, with feet first (The head was outside the magnet). The extremity was in slight external rotation of approximately 15 degrees and the affected extremity in the knee coil. Pulse sequences used for conventional MRI were sagittal T1 weighted fast spin echo (FSE) images with repetition time (TR) 600ms and echo time (TE) 15ms, axial and sagittal T2 weighted FSE (with TR 4000ms and TE 90ms), sagittal proton density weighted images with fat suppression (with TR over 4000ms and TE 30ms), coronal T2 short time for inversion recovery (STIR) images (with TR over 4000ms and TE 120ms), and axial gradient (flip angle 30, with TR 440ms and TE 13ms). DW-MRI was obtained at the section level where the largest transverse section of the lesion was detected on conventional MRI. DW-MRI was obtained using multi -slice spin –echo single –shot echo planar imaging in the sagittal plane. For each patient, diffusion weighted images and ADC maps was obtained by applying diffusion sensitive gradients in three orthogonal directions (x, y and z) with TR 1900 ms, TE 100ms and b-values (250-500-800 s/mm2), slice thickness was 4mm in all sequences, inter slice gap 1mm, and matrix 256x256. Total scanning time was approximately 20 minutes. Measurement of the ADC values was done as follows: a region of interest (ROI) was placed within the ACL midportion (mainly posterolateral bundle)

to measure the signals of the DWI and ADC values on the oblique sagittal DWI with b value of 500 and at the site of ACL tear. The average diameter of the ROI was 3 mm2 (minimum: 2 mm2, maximum: 4 mm2). The average values were calculated and tabulated (quantitative assessment). Cases with bone marrow contusion, region of interest of 75 mm2 was placed in regions of bone marrow lesions and normal regions to calculate the ADC values. Also, we measured the size of bone marrow contusion in both DWI-derived ADC maps and FS PD-weighted images.

Statistical analysis

Statistical analysis was done by SPSS v26 (IBM Inc., Chicago, IL, USA). Quantitative variables were presented as mean and standard deviation (SD) and compared between the three groups utilizing ANOVA (F) test with post hoc test (Tukey). Qualitative variables were presented as frequency and percentage (%) and were analyzed utilizing the Chi-square test. Sensitivity: probability that a test result will be positive when the disease is present (true positive rate). Specificity: probability that a test result will be negative when the disease is not present (true negative rate). Positive predictive value: probability that the disease is present when the test is positive. Negative predictive value: probability that the disease is not present when the test is negative. Accuracy: overall probability that a patient is correctly classified. A two tailed P value < 0.05 was considered statistically significant.

RESULTS

Demographic characteristics, clinical manifestation, clinical test, the conventional, diffusion MRI findings regarding the ACL injuries, and management of ACL tears of the studied patients were enumerated in

Table 1.

The relationship between the demographic data, ADC values, and the ACL findings in DWI MR imaging was insignificant. A comparison between conventional MRI and DWI findings for ACL tear was enumerated in this table. **Table 2**

Association knee injuries by the conventional and diffusion weighted MRI of the studied patients was enumerated in **Table 3.**

Associated knee findings, direct and indirect signs of the ACL tears by the conventional MRI of the studied patients were enumerated in **Table 4.**

ADC value was significantly higher in bone marrow edema than normal bone marrow. **Table 5**

The diagnostic accuracy of conventional MRI and DWI for ACL tear with reference to the arthroscopy diagnosis. The conventional MRI showed 67% sensitivity and 50% positive predictive value while specificity and negative predictive value were not calculated because the 3 cases that were categorized by arthroscopy as partial tear were seen as sprain by the conventional MRI. On the other hand, DWI showed 100% sensitivity, specificity, positive and negative predictive values. **Table 6**

Case 1: A 30-year-old female patient, presented clinically with left knee pain and swelling with a history of left knee trauma. Final MRI diagnosis: A partial tear in the left ACL (as shown on DWI), torn grade 3 in PHMM, MCL grade 1 sprain, and mild left knee synovial effusion. Final arthroscopic findings are in keeping with those of DWIs. **Figure 1**

Case 2: A 53-year-old female patient, presented clinically with right knee pain, twisting, lateral deviation of knee with movement and history of knee trauma. Final MRI diagnosis: a partial tear in the right ACL and osteoarthritic changes of the right knee joint. Final diagnosis by follow up after physiotherapy and medical treatment is keeping with MRI findings. **Figure 2**

Table 1: Demographic characteristics, clinical manifestations, clinical tests, the conventional, diffusion MRI findings regarding the ACL injuries and management of ACL tears of the studied patients

		N=30
Age (years): **16-20** **>20-30** **>30-40** **>40-53**		 6(20.0%) 9(30.0%) 8(26.7%) 7(23.3%)
Sex	**Female**	12(40.0%)
	Male	18(60.0%)
Side	**Right knee**	19(63.3%)
	Left knee	11(36.7%)
Clinical manifestations	**Pain**	30(100.0%)

	Joint instability	10(33.3%)
	Swelling	9(30.0%)
	Limitation of movement	6(20.0%)
	Click sensation	4(13.3%)
Clinical tests	**Lachman test**	22(73.3%)
	Pivot shift test	10(33.3%)
Conventional MRI	**Partial tear**	15(50.0%)
	Complete tear	8(26.7%)
	Sprain	7(23.3%)
DWI	**Partial tear**	19(63.3%)
	Complete tear	9(30.0%)
	Intact fibers	2(6.7%)
Management of ACL tears	**Medical treatment and physiotherapy**	21(70.0%)
	Arthroscopy	9(30.0%)
	Complete tear	6(66.66%)
	Partial tear	3(33.33%)

Data is presented as frequency (%). MRI: Magnetic resonance imaging, ACL: Anterior cruciate ligament, DWI: diffusion-weighted imaging.

Table 2: Association between gender, age, the ADC values of the complete and partial ACL tears findings in diffusion weighted MRI of the studied patients and comparison between conventional MRI and DWI findings for ACL tear

	Complete tear (n=9)	**Partial tear (n=19)**	**Intact fibers (n=2)**	**Test of sig.**	**P**
Gender					
Male	7(77.8%)	10(52.6%)	1(50.0%)	X^2=1.875	0.428
Female	2(22.2%)	9(47.4%)	1(50.0%)		
Age					
16-20	2(22.2%)	4(21.1%)	0(0.0%)	X^2=4.052	0.744
>20-30	4(44.4%)	4(21.1%)	1(50.0%)		
>30-40	2(22.2%)	6(31.6%)	0(0.0%)		
>40-53	1(11.1%)	5(26.3%)	1(50.0%)		
ADC values of the complete and partial ACL tears findings					
ADC x 10 $^{-6}$(mm^2/s)	1752.46±289.17	1661.32±29.28	1676.20±615.16	F=0.1369	0.872
MRI	8(88.9%)	0(0.0%)	0(0.0%)	--	--
	1(11.1%)	14(73.7%)	0(0.0%)	--	--
	0(0.0%)	5(26.3%)	2(100.0%)	--	--

Data is presented as frequency (%). MRI: Magnetic resonance imaging. ADC: Apparent diffusion coefficient.

Table 3: Associated knee injuries by the conventional and diffusion weighted MRI of the studied patients

		Conventional MRI (n=30)	**Diffusion weighted MRI (n=30)**
Meniscal injuries	**Meniscal tear:** **PHMM** **PHLM**	 5(16.7%) 1(3.3%)	 5(16.7%) 1(3.3%)
	Meniscal degeneration: **PHMM**	 6(20.0%)	 2(20.0%)
Bone marrow contusion, cm	**2.77**	1(3.3%)	1(3.3%)
	2.77	1(3.3%)	1(3.3%)
	Femur 2.22, Tibia 1.55	1(3.3%)	1(3.3%)
	2.5	1(3.3%)	1(3.3%)
Fracture	**Lateral tibial plateau non-displaced fracture**	1(3.3%)	1(3.3%)
MCL injury	**Grade 1 sprain**	5(16.7%)	--
	Grade 2 sprain	2(6.7%)	--
Post lateral corner injury	**Arcuate ligament tear and popliteus muscle grade 1 injury**	1(3.3%)	--

Data is presented as frequency (%). MRI: Magnetic resonance imaging, MCL: Medial collateral ligament.

Table 4: Associated knee findings, direct and indirect signs of the ACL tears by the conventional MRI of the studied patients

		N=30
Associated knee findings by the conventional MRI		
Synovial effusion		13(43.33%)
OA		4(13.3%)
Direct signs of the ACL tears by the conventional MRI		
ACL discontinuity and signal intensity	**Abnormal signal**	30(100.0%)
	Partial discontinuity	15(50.0%)
	Complete discontinuity	8(26.7%)
Empty notch		8(26.7%)
Indirect signs of the ACL tears by the conventional MRI		
Anterior tibial translation		8(26.7%)
PCL buckling		1(3.3%)
Deep femoral sulcus sign		1(3.3%)

ent, ACL: Anterior cruciate ligament, ADC: Apparent diffusion coefficient, OA: Osteoarthritis.

Table 5: Mean ADC value of bone marrow edema and normal bone marrow

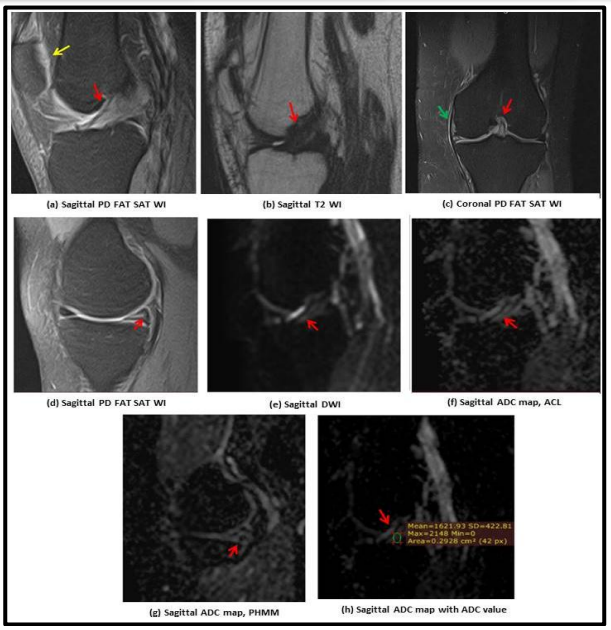
	Normal bone marrow (n=26)	Bone marrow edema (n=4)	t	P
ADC x 10^{-3} (mm^2/s)	0.064±0.146	1.084±0.687	7.198	**<0.001***

Data is presented as mean ± SD. * Significant P value < 0.05. ADC: Apparent diffusion coefficient.

Table 6: The diagnostic accuracy of conventional MRI and DWI for ACL tear with reference to the arthroscopy diagnosis

		Complete (N=6)	Partial (N=3)	Sensitivity	Specificity	PPV	NPV	P
MRI	**Complete**	6(100.0%)	0(0.0%)	--	67%	50%	--	1.00
	Sprain	0(0.0%)	3(100.0%)					
DWI	**Complete**	6(100.0%)	0(0.0%)	100%	100%	100%	100%	1.00
	Partial	0(0.0%)	3(100.0%)					

MRI: Magnetic resonance imaging, DWI: Diffusion-weighted imaging, PPV: Positive predictive value, NPV: Negative predictive value.



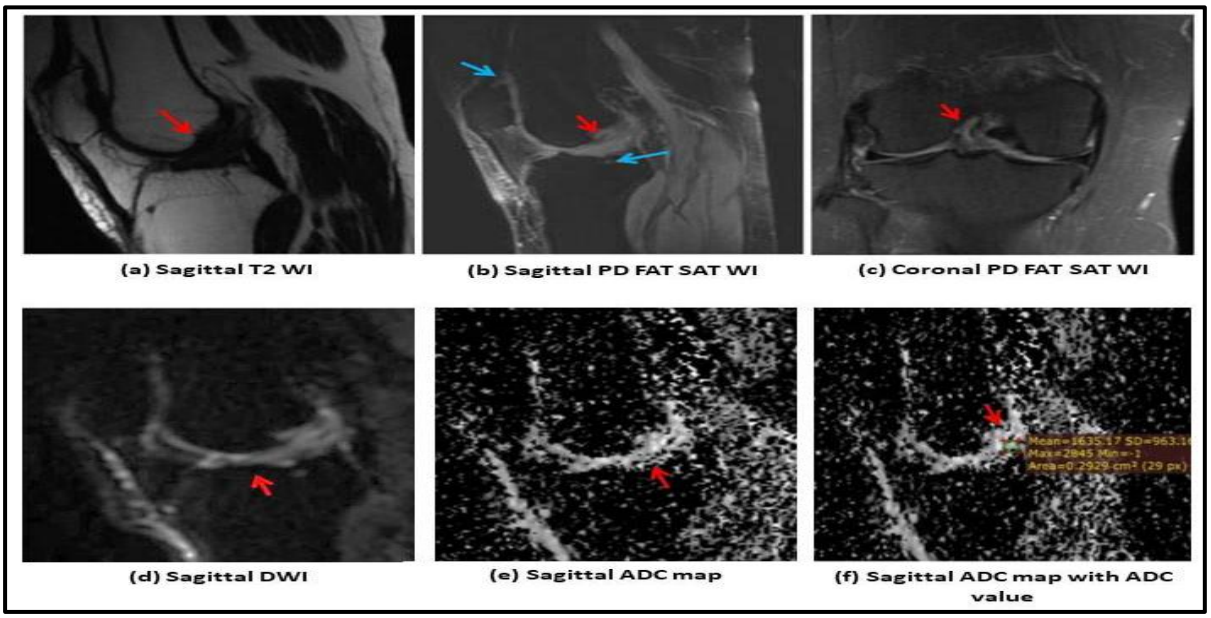


Figure Legends:

Figure 1: Conventional magnetic resonance imaging of the left knee joint showed thickening and abnormal high signal intensity in the left anterior cruciate ligament with intact its fibers, suggesting anterior cruciate ligament sprain (red arrow in a, b and c), grade 1 sprain in medial collateral ligament (green arrow in c), mild left knee joint synovial effusion (yellow arrow in a) with horizontal tear grade 3 in the PHMM, reaching to its superior articular surface (red arrow in d). Diffusion-weight imaging and apparent diffusion coefficient map with b value=500 showed a partial disruption of the posterior-lateral bundle of the left anterior cruciate ligament fibers (red arrow in e, f) and confirmed tear grade 3 in the PHMM (red arrow in g). Mean ADC value at the site of anterior cruciate ligament tear was (1621.93 x 10-6 ± 422.81 mm^2/s) (h) Normal anterior cruciate ligament with b value 500 of intact anterior cruciate ligament measuring about (1676.20 x 10-6± 615.16 mm^2/s).

Figure 2: Conventional magnetic resonance imaging of the right knee joint showed thickened and abnormal high signal intensity in anterior cruciate ligament with partial disruption of its fibers (red arrows in a, b and c), anterior tibial translation, measuring about 5.69mm (d), degeneration grade 2 in PHMM (red arrow in e), and moderate right knee joint synovial effusion (yellow arrow in e). DWI and ADC map with b value =500 show altered signal in the anterior cruciate ligament fibers (red arrows in f and g) with mean apparent diffusion coefficient value of the torn ligament measuring about (1622.08 x 10-6 ±708.15 mm^2/s)

DISCUSSION

DWI is based on the diffusion of free water in tissue. This property has been applied for early diagnosis of ischemic strokes and to characterize neoplastic tissue, these sequences can reflect tissue richness [6].

In our study, 73.3% of patients showed positive Lachman test, while 33.3% of patients showed positive pivot shift test which coincide with Lane et al. [10] tabulated 13 examination techniques for the pivot shift test

Our study showed that all cases have abnormal signal intensity, 26.7% of cases showed complete ACL discontinuity and 50% of cases showed partial discontinuity. This matched with the study of NG et al. [11].

In our study, DW images and ADC image maps were gained in the sagittal plane in similar positions used in the T2 sequences. DWI was done with multiple b values from b 0 to b 1000 to obtain the best image which achieved with b value 500 and this agreed with the study of Ali et al. [12].

Our study exhibited partial ACL tears on conventional MRI while complete tears were shown on DW sequence. Another 5 cases exhibited ACL sprain on conventional MRI and partial tear on DW sequence. Intraoperative findings showed a partial ACL tear in 3 cases. Moreover, two cases revealed ACL sprain on conventional MRI and intact fibers on DW sequence, suggesting that DW sequence could be more reproducible in distinguishing between complete and incomplete ACL tears.

In the present work, the average ADC values were calculated, and there were non-significant differences between the mean ADC values of complete ACL tear (1752.46± 289.17 mm2/s), partial tear (1661.32± 29.28 mm2/s) and the normal ACL (1676.20±615.16 mm2/s). These results agreed with Park et al. [13] found the sensitivity and accuracy of DWI are lower than the conventional MRI therefore adding DWI to conventional MR sequences did not enhance diagnostic performance. This had been highlighted in the study of Delin et al. [6] reported that how to place an ROI precisely on the ACL without extending into the edema and causing error.
In present study we compared the efficacy of DWI and conventional MRI in diagnosis of ACL tears, sensitivity was 67% for conventional MRI and 100% for DWI with PPV50% for MRI and 100% for DWI.
In the current study the main knee injuries associated with traumatic ACL tear were meniscal tears in 20% of cases, bone marrow contusion in 13.3% of cases, MCL injury in 23.4% of cases, the most common associated finding was synovial effusion in 43.33% of patients and OA in 13.3% of patients and this matched with the study of Stevens and Dragoo [14].
The most common entangled structure was the menisci, accounting for 20% of associated pathologies, with 16.7% of the patients had medial meniscus injury (PHMM) and 3.3% showing lateral meniscus injury (PHLM) indicating that, injuries of PHMM more than the injuries of PHLM in traumatic knee injury. This was in harmony with Aydin et al. [15] and Naraghi and White [16], reported more injury of the medial meniscus than the lateral, Like Hansford and Yablon [17], found that the combined injury of ACL and MCL is commonly diagnosed during conventional examination of the knee.

In our work, we found the size of bone marrow edema appears larger on DWI than conventional MRI also; ADC values in bone marrow edema were higher than in normal bone marrow. This agreed with the hypothesis by Klengel et al. [18] reported that single-shot echoplanar imaging–derived ADC maps are more sensitive than FS PD-weighted TSE images for the detection of bone marrow lesions and do not rely on spectral fat suppression.

Limitations of the study included that the sample size was relatively small. Association of two different reference standards in ACL tears: arthroscopy and follow up because of the invasive nature of arthroscopy it was not usually used for diagnostic purpose alone. Low spatial resolution of DWI and ADC mapping so the images obtained were of low quality also DWI is easily affected by motion artifact which can be solved by using a 3 Tesla or higher MRI that enable the detection of more lesions and better resolution. We did not involve axial and coronal DW images in this work. It was tough to place an ROI exactly on the ACL without extending into the edema and causing errors. Also, interposition of the fat component or hemorrhage between the torn ligaments might have affected the ADC values.

CONCLUSION

Adding DWI to conventional MRI sequences in differentiation between complete and partial ACL tears improves the diagnostic performance, but quantitative evaluation has no role as there is no significant differences between the mean ADC values of torn ligament and normal ligament. ADC maps are more sensitive than FS-PD-weighted images for the detection of bone marrow (BM) contusion; hence, they represent a valuable add-on in trauma imaging protocols. DWI and ADC mapping could easily visualize meniscal tears, bone marrow edema and/or contusion, and knee joint synovial effusion as efficient as conventional MRI.

List of Abbreviations:
DWI: Diffusion weighted imaging.
MRI: Magnetic resonance imaging.
ACL: Anterior cruciate ligament.
OA: osteoarthritis.
ADC: Apparent diffusion coefficient.
SS-EPI: single shot echo planar imaging.
BML: Bone marrow lesions
MCL: Medial collateral ligament
FSE: fast spin echo
TR: repetition time

Declarations

Ethical approval and consent to participate:
The study was done from July 2021 to September 2024 after approval from the Ethical Committee Tanta University Hospitals, Tanta, Egypt. Approval Code: (34676/5/21). An informed written consent was obtained from the patients or relatives of the patient.

Consent for publication:
Not applicable

Availability of data and materials:
Data is available on reasonable requests from the corresponding author.

Competing interests:
The authors have no financial or proprietary interest in any material discussed in this article.

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Authors' contribution:
All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [A.E.E.S.], [H.M.A.S.] and [A.E.K.]. The first draft of the manuscript was written by [H.M.S.E.] and all authors commented on previous versions of the manuscript. All authors read

and approved the final manuscript

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