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ORIGINAL ARTICLE

Added Value of Qualitative and Quantitative Diffusion Weighted Magnetic Resonance Imaging (DWI-MRI) in Assessment of Non-neoplastic Achilles Tendon Related Pathologies

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ABSTRACT

Background: It has been demonstrated that magnetic resonance imaging (MRI) techniques of Diffusion Weighted Imaging (DWI) and Apparent Diffusion Coefficient (ADC) mapping can facilitate the identification of structural and biochemical alterations in tissue, offer early detection of pathological changes, and track tissue damage. Purpose of this study was to assess how useful DWI and ADC mapping are for identifying Achilles tendon (AT) disorders.

Methods: This case-control study was done on 60 participants; 30 symptomatic patients with suspected AT pathology and 30 healthy volunteers as control group. Subjects underwent MRI of the ankle with multiple sequences (T1, T2, STIR, proton density), complemented by DWI and ADC images.

Results: Final MRI diagnosis was tendinopathy, inflammation, partial tear, complete tear and Haglund's syndrome. DWI demonstrated high sensitivity in detecting pathology of Achilles tendon with relatively lower specificity. ADC measurement had statistically significant higher value comparing the patients and healthy controls (p value <0.001.) with sensitivity (100%) and specificity (96.67%). Combining DWI& ADC with conventional MRI improved the diagnostic accuracy sensitivity (100%), specificity (75%), accuracy (95%), PPV of (78 %) and NPV of (100%). Agreement between DWI/ADC and reference standard was good.

Conclusions: Quantitative ADC mapping provides valuable complementary information to conventional MRI in diagnosing AT pathologies. While DWI offers good sensitivity and diagnostic accuracy, ADC analysis helps distinguish true diffusion restriction from T2 shine-through effects. In addition, diffusion MRI remains limited by lower spatial resolution and image quality compared with conventional MRI images.

Keywords: DWI MRI, ADC mapping, Conventional MRI, Achilles tendon.

INTRODUCTION

The Achilles tendon (AT) is the thickest and the most powerful tendon; it plays a vital role in the biomechanics of the lower extremities and in activities like walking, running, and jumping. In addition to being the strongest tendon in our body, because of its size and functional overload, the AT is the most injured tendon. AT is prone to both acute and chronic damage and is directly or indirectly involved in many pathologies of the foot and ankle [1]. Achilles tendon disorders can affect different age groups, increased involvement in sporting activities over the past years lead to increased overuse injuries also complete or spontaneous ruptures of the AT are found [2]. Achilles tendinopathy is characterized by localized pain and functional impairment due to mechanical loading, its etiology has multiple factors affecting it including repeated overloading, negative drug effects, ageing and various comorbidities [3].

Diagnosis of Achilles tendon pathologies relies on clinical data and physical examination [4]. While conventional radiography is the first step in evaluation by excluding osseous injury, it is often insufficient for detecting subtle tendon or ligament abnormalities, particularly in the absence of bone avulsions or significant effusions [5]. In this context, accurate imaging is crucial, as misdiagnosis of subtle tendon pathology may alter treatment planning [5]. Among the different imaging techniques available, magnetic resonance imaging (MRI) has been well recognized as a reference tool in identifying and diagnosing AT pathologies including tears, micro-tears and degenerative changes [2]. As MRI provides high tissue contrast and resolution it allows detailed assessment of tendon morphology and pathology and may decrease the need for invasive diagnostic procedures [6]. With the evolving technology, new MRI sequences have been designed to improve the diagnostic accuracy of routine MRI protocol particularly for musculoskeletal pathologies involving muscles, nerves, ligaments and tendons [7]. These new imaging sequences provide a more accurate assessment of pathology, specifically in areas of muscles, nerves, ligaments and tendons [2]. Diffusion Weighted Imaging (DWI) and Apparent Diffusion Coefficient (ADC) mapping are advanced MRI methods that use water molecules' thermal motion to evaluate the tissue microstructure [8]. DWI provides qualitative information on tissue organization [8], while the quantitative ADC measurements provide early diagnostic indicators for the existence of pathogenic alterations and monitoring tissue damage [9]. Although numerous studies have explored the role of MRI in diagnosing AT lesions, limited evidence exists regarding the contribution of DWI and ADC mapping for specific AT pathologies. Therefore, this study was designed to assess the added value of DWI and ADC mapping in diagnosing Achilles tendon injuries, in comparison with conventional MRI sequences.

METHODS

This prospective study was conducted in the Radiology Department at our institute during the period between January 2024 and January 2025. The protocol was approved by the Institutional Review Board (ZU-IRB#11165, approved on October 4,2023). The Helsinki Declaration of the World Medical Association for experiments involving humans was followed in the conduct of this study. Sixty participants were included; 30 symptomatic patients for AT pathology or suspected AT injury, their ages ranged between 21 to 65 years. In addition, to 30 age matched healthy volunteers serving as a control group, their ages ranged between 20 to 65 years. Inclusion criteria included symptomatic patients presenting with signs suggestive of AT pathology (e.g., pain, swelling, tenderness) or suspected AT injury on initial clinical examination. Exclusion criteria included contraindications to MRI such as cardiac pacemakers or metallic implants and patients refused to be enrolled in the study. All patients were subjected to clinical assessment including full medical history (onset, mechanism of injury, history of previous trauma) and local examination of affected ankle for site of trauma, erythema, swelling, and joint instability or stiffness. Magnetic resonance imaging was done, using Philips Achieva 1.5 T scanner. Multi-planner imaging of the injured ankle in different planes was performed using the following sequences: T1-weighted imaging: TR 400ms, TE 12ms, slice thickness 3 mm, FOV 12 cm, T2-weighted imaging: TR 4500 ms, TE 81 ms, slice thickness 3 mm, FOV 12 cm, Proton density FAT SAT imaging: TR 1000 ms, TE 10–30 ms, slice thickness 3 mm, FOV 12 cm, STIR imaging: TR 3800 ms, TE 46 ms, slice thickness 3 mm, FOV 12 cm, Diffusion-weighted imaging (DWI): TR 2000–7500, TE 65 ms, FOV 200 × 200 mm, matrix 80 × 112, slice thickness 3 mm, interslice gap 1 mm, b-values = 600, 800, and 1000 s/mm², ADC Mapping: Apparent diffusion coefficient (ADC) values were measured by manually placing regions of interest (ROIs) within the lesions on ADC map images.

Image Interpretation

The obtained DWI, ADC & conventional magnetic resonance images were independently assessed on separate sessions by two radiologists, each with more the 10

years of experience in ankle imaging. Both radiologists were blind to clinical data. Evaluation included tendon boundaries, consistency, size, shape, signal characteristics, and quantitative ADC values. Conventional MRI sequences were additionally assessed for lesion site, laterality, and type of AT abnormality.

Gold Standard

Surgical repair was done for cases with complete tendon tear, Arthroscopy was done for cases of partial tendon tear, comparison with clinical diagnosis and follow-up findings were used in cases of inflammation and tendinopathy.

Statistical analysis

The collected data were coded, entered, and analyzed by computer using a database software program, IBM SPSS 23.0 for windows (SPSS Inc., Chicago, IL, USA). One way analysis of variance (ANOVA) test used to analyze the difference between means of independent variables of more than two groups. p value < 0.05 was considered significant. Chi-square [X2] test is a non-parametric test that is used to study if there is a relationship between two or more categorical variables. The ROC curve (receiver operating characteristic) gives a useful way to evaluate the sensitivity and specificity for quantitative diagnostic measures that categorize cases into one of two groups.

RESULTS

Regarding demographic data, patients' ages ranged from 21 to 65 years (mean ± SD, 36.5 ± 10.9), with 14 males (46.7%) and 16 females (53.3%). The control group ranged from 20 to 65 years (mean ± SD, 32.7 ± 12.5), comprising 12 males (40%) and 18 females (60%). Regarding qualitative DWI and quantitative ADC Findings, all examined Achilles tendons in the patient group demonstrated abnormal high signal intensity on DWI (100%). Of these, 19 patients (63.3%) had non-insertional lesions, while 11 (36.7%) had insertional lesions. Complete tendon tear was suspected in 6 cases based on loss of tendon continuity [Table S1]. On qualitative assessment, all patients showed abnormal high signal on both DWI and ADC (100%), consistent with T2 shine-through effect rather than true diffusion restriction. Facilitated diffusion was observed in all cases, with no restricted diffusion detected [Table 1]. The mean ADC values were significantly higher in patients compared to controls ($p < 0.001$) [Table 2]. Final gold standard diagnoses in the patient group included: 3 normal cases (10%), 10 cases of tendinopathy (33.3%), 6 partial tears (20%), 6 complete tears (20%), 4 cases of inflammation (13.3%) and one patient with Haglund's syndrome (3.3%) [Table S2]. Comparing findings with DWI revealed 3 false positive cases diagnosed as normal by DWI. Regarding the type of pathology, DWI cannot differentiate between different types except for complete tear where discontinuity of the tendon is visible (6 cases). As regards correlation with gold standard, there was a statistically significant association between ADC values and gold standard diagnosis. ADC values were lower in patients with normal tendons and inflammation, and progressively higher in tendinopathy, partial tears, and complete tears. Agreement between DWI/ADC findings and gold standard diagnosis was excellent ($\kappa = 0.925$, $p < 0.001$) [Table 3]. As regards ROC curve analysis, Receiver operating characteristic (ROC) analysis demonstrated that ADC values had excellent diagnostic performance in distinguishing patients from healthy controls. The optimal cutoff value was 0.063×10^{-3} mm^2/s, yielding a sensitivity of 100% and specificity of 96.67%, with an AUC of 1.00, P Value <0.001 [Table 4]. Subgroup ROC analysis provided cutoff values of 0.06, 0.49, 1.27, and 1.51×10^{-3} mm^2/s for differentiating inflammation, tendinopathy, partial tear, and complete tear, respectively. The combined use of DWI and ADC maps in detecting Achilles tendon pathology demonstrated a sensitivity of 100%, specificity of 75%, accuracy of 95%, positive predictive value of 78%, and negative predictive value of 100% [Table S3]. Our cases are illustrated in [Figure 1, 2, 3].

Table (1): DWI and ADC findings among the patients group

Variables *(n. %)*		**Patients group (n=30)**
DWI & ADC	**No abnormal signal**	**0 (0%)**
	High signal	**30 (100%)**
	Facilitated	**30 (100%)**
	Restricted	**0 (0%)**

Table (2): ADC value among the studied groups

Variables		**Patients group (n=30)**	**Control group (n=30)**	**P Value**
ADC value	***Mean ± SD***	**0.93 ± 0.51**	**0.05 ± 0.009**	**<0.001**
	Range	**(0.13 – 1.6)**	**(0.03 – 0.06)**	

*Student T-test, Non-significant: P >0.05, Significant: P ≤0.05

Table (3): Association between ADC value and gold standard diagnosis among the studied participants

Types of pathology at Achilles tendon *(n. %)*	***N (%)***	**ADC value $x10^{-3}$ mm^2/sec *Mean ± SD***
Normal	**33 (55%)**	**0.04 ± 0.22**
Inflammation	**4 (6.7%)**	**0.15 ± 0.02**
Tendinopathy	**10 (16.7%)**	**0.69 ± 0.06**
Partial tendon tear	**7 (11.7%)**	**1.29 ± 0.02**
Complete tear	**6 (10%)**	**1.57 ± 0.03**
P value		**<0.001**

*One way ANOVA test, Non-significant: P >0.05, Significant: P ≤0.05

Table (4): ROC curve analysis of ADC value in differentiating healthy controls from patients

Variables	**Cut point**	**Sensitivity (%)**	**Specificity (%)**	**PPV (%)**	**NPV (%)**	**AUC (%)**	**P Value**
ADC value	0.063	100%	96.67%	96.77%	100%	1.00	<0.001

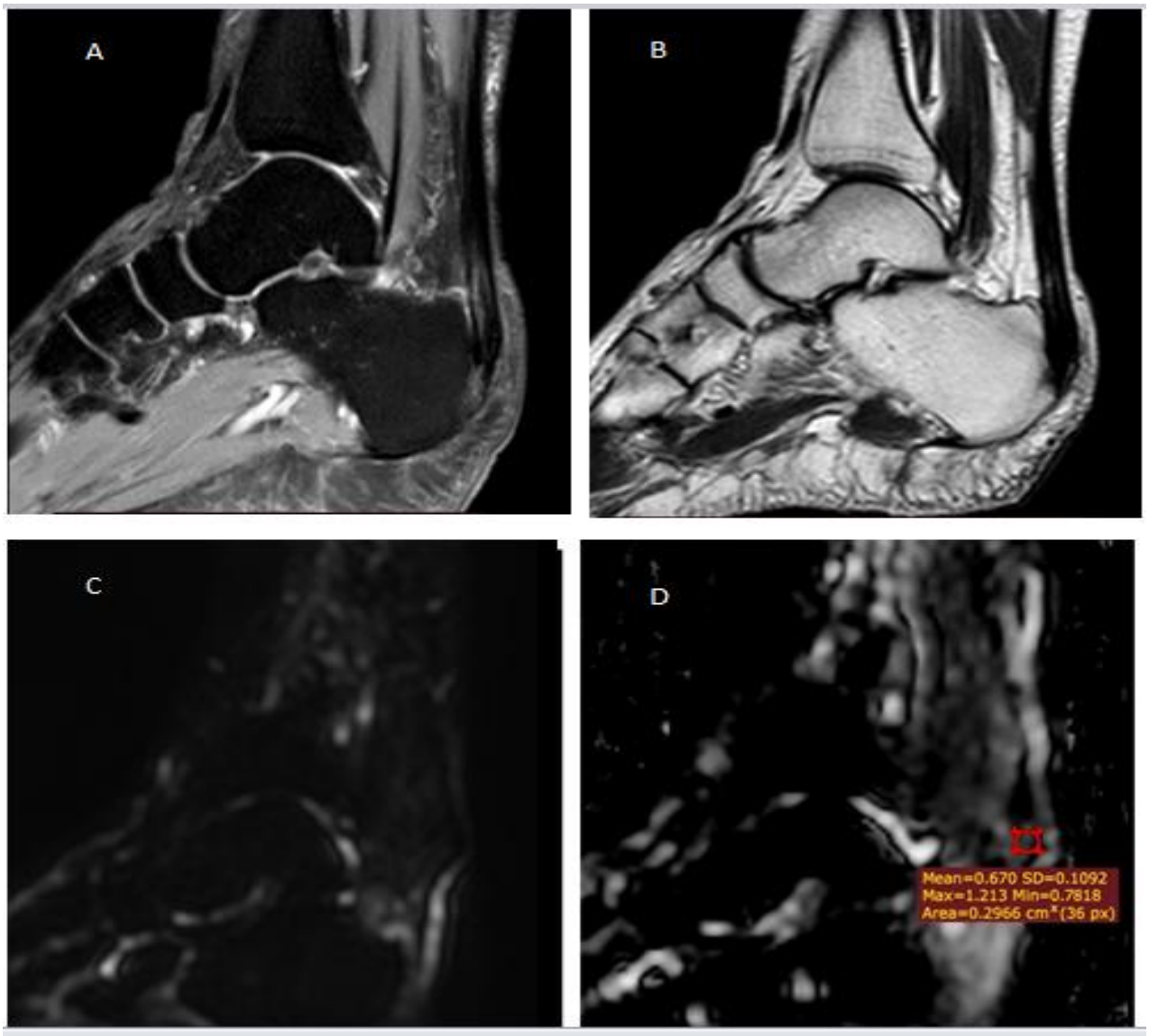

Figure (1): 40-year-old male patient presented with posterior ankle pain associated with difficult walking. Image A (Sagittal PD fat-sat) and B (Sagittal T2WI) showing intra-substance abnormal high signal intensity with mild thickening affecting the Achilles tendon, Intact fibrillar continuity of Achilles tendon along its length, no joint effusion, preserved bone marrow signal of the insertion site at calcaneus bone, normal bone marrow signal of other tendons and ligaments. Image C: (Sagittal DWI) showing intra-substance abnormal high signal intensity and thickening of Achilles tendon. Image D (Sagittal ADC) showing intra-substance abnormal high signal intensity and thickening of Achilles tendon with ADC value of 0.67 x10-3 mm2/sec. Conclusion: Achilles tendinopathy, no associated DWI restriction.

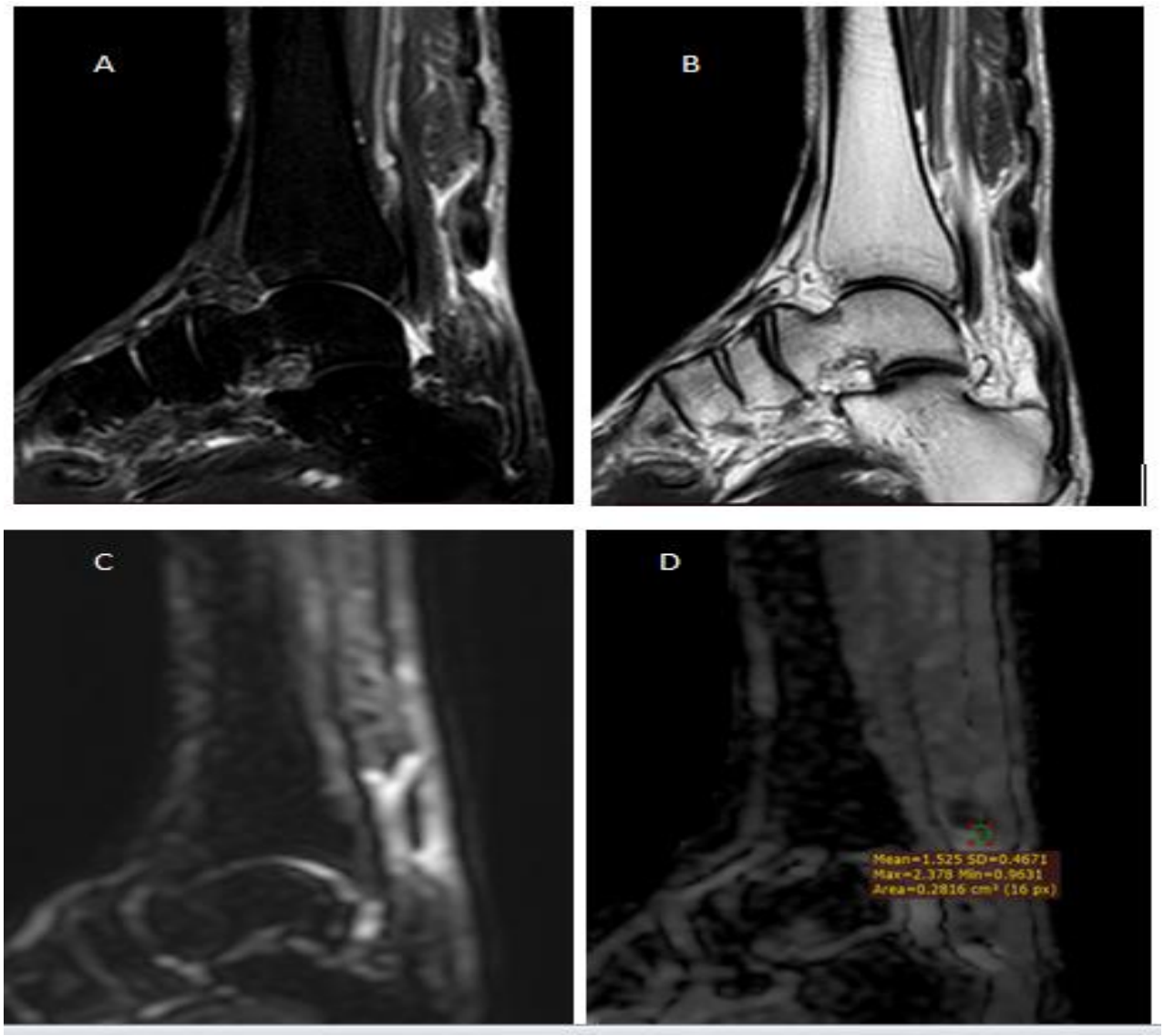

Figure (2): 48-year-old male patient presented with post traumatic posterior ankle pain and limitation of movement. Image A (Sagittal STIR) and B (SagittalT2WI) showing complete loss of the continuity of tendon Achilles fibers with fluid filled gap and fibers retraction. Image C (Sagittal DWI) showing abnormal high signal intensity with complete loss of the continuity of tendon Achilles fibers and fluid filled gap and fibers retraction. Image D (Sagittal ADC) showing abnormal high signal intensity with complete loss of the continuity of tendon Achilles fibers and fluid filled gap and fibers retraction with ADC value of 1.525 $x10^{-3}$ mm^2/sec. Conclusion: complete tendon Achilles tear, No DWI restriction.

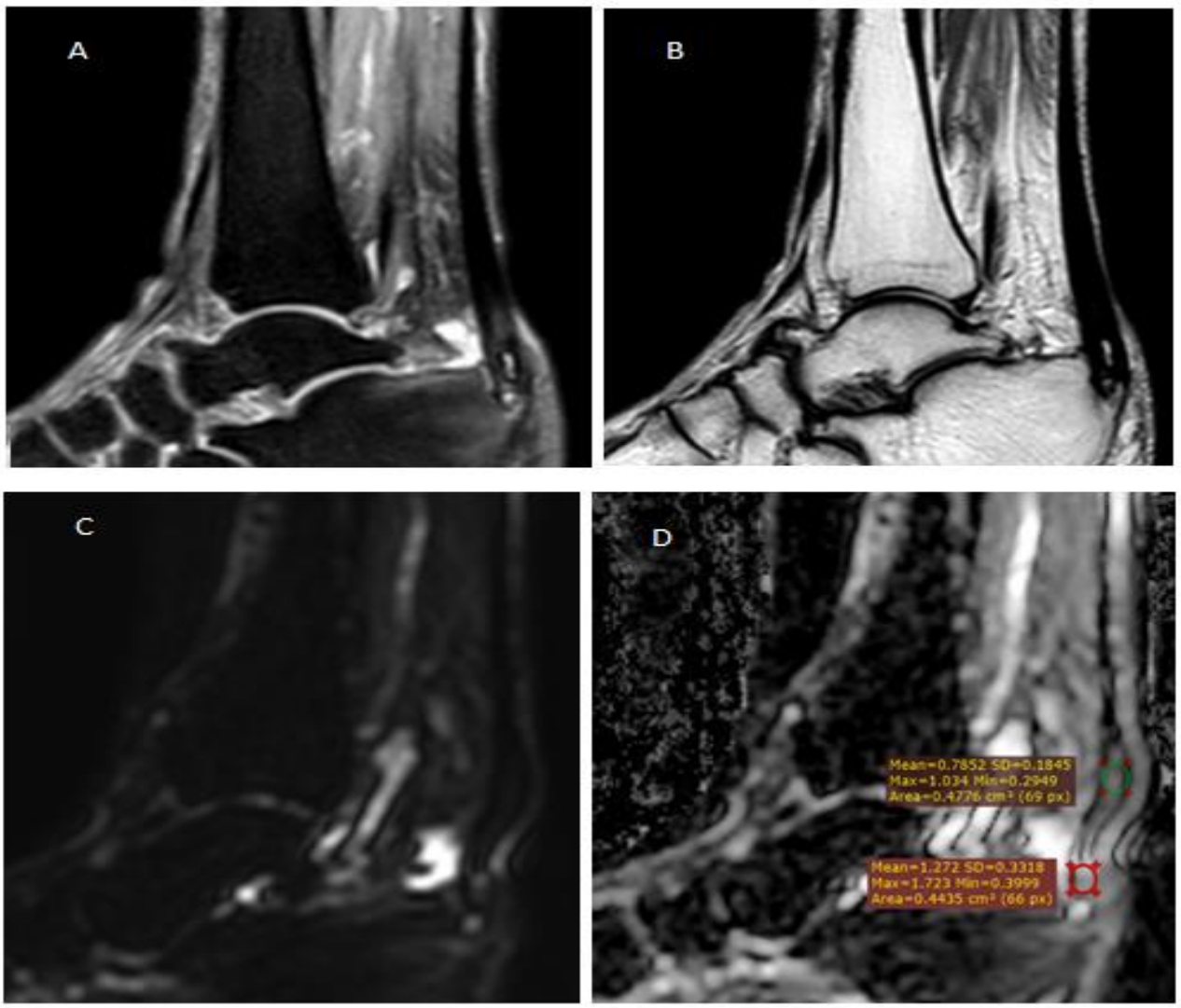

Figure (3): 29 year old male patient presented with posterior ankle pain associated with swelling and difficult walking, Image A (Sagittal PDWI fat-sat) and B (Sagittal T2WI) showing thickening and abnormal intra-substance high signal intensity along its length along with another focal area of abnormal increased signal intensity at its insertion site displaying high SI at PDWI and T2WI, with partial loss of the fibrillar continuity, associated retro-calcaneal bursitis and postero-superior calcaneal exostosis. Image C (Sagittal DWI) showing thickening and abnormal intra-substance high signal intensity along its length along with another focal area of abnormal increased signal intensity at its insertion site. Image D (Sagittal ADC) showing thickening and abnormal intra-substance high signal intensity along its length with ADC value of 0.78 $x10^{-3}$ mm^2/sec with another focal area of abnormal increased signal intensity at its insertion site with ADC value of 1.27 $x10^{-3}$ mm^2/sec. Conclusion: Haglund's syndrome is complicated by partial thickness tear, no DWI restriction.

DISCUSSION

Diffusion-weighted magnetic resonances imaging (DWI) and apparent diffusion coefficient (ADC) mapping, relatively recent additions to musculoskeletal MRI sequences, are being increasingly employed to enhance clinical diagnosis and decision-making. DWI and ADC are rapid, noninvasive and contrast-free imaging techniques that provide both qualitative and quantitative information by analyzing the motion of water molecules within tissues. These methods offer insights into cell density, tissue microstructure, and organization, aiding in the differentiation between normal and pathological tissues [10]. DWI has gained popularity in musculoskeletal

radiological imaging because of its undeniable role in diagnosis and assessment of therapeutic response [11]. This study demonstrates that diffusion-weighted imaging (DWI) and apparent diffusion coefficient (ADC) mapping can effectively differentiate between healthy and pathological Achilles tendons (AT). The findings show significantly higher ADC values in pathological tendons compared to healthy controls, with ADC values correlating with the severity of tendon pathology. DWI and ADC mapping exhibited high diagnostic performance, with sensitivity and specificity values of 100% and 75%, respectively, suggesting that these imaging modalities may serve as valuable adjuncts to conventional MRI. In our study, gold standard findings revealed that 45% of the participants had Achilles tendon (AT) pathology. Tears (partial and complete) were the most common (40%), followed by tendinopathy (33.3%), inflammation (13.3%) and Haglund's syndrome (3.3%). Haglund's is a deformity accompanied by degeneration of the tissue of the Achilles tendon due to friction against the exostosis [12]. Non-insertional tendinopathy was the most frequent location of injury (63.3%), consistent with previous study [13]. The most common MRI features of injured tendons were thickened tendons with intra-tendinous high signal intensity on T2W images, tendon discontinuity with irregular or wavy contours, and fluid accumulation within the tendon sheath [9]. Routine MRI remains the gold standard for assessment and diagnosis of musculoskeletal disorders, DWI can provide complementary information, improve lesion characterization, and guide earlier treatment decisions [15, 16]. In the present study, all patients demonstrated abnormal high signal intensity on DWI and ADC. When correlated DWI & ADC findings with the gold standard diagnosis, DWI can detect presence of pathology regardless of its nature in AT in cases of inflammation, tendinopathy and partial tear but correctly identified cases with complete tears (4 cases). Regarding the quantitative measurement of ADC values, we found that ADC values calculated for the healthy AT group were presented as mean and SD of 0.05 ± 0.009 ($\times 10^{-3}$mm2/s). Our findings agreed with Al Mulla et al. [2], who reported that the mean ADC value and SD of 0.091 ± 0.116 ($\times 10^{-3}$mm2/s) in healthy AT. We found a statistically significant higher ADC value between AT pathology and the healthy controls 0.93 ± 0.51 ($\times 10^{-3}$mm2/s) more over the ADC values were significantly associated with the type of pathology; lower values were observed in normal tendons and inflammation, while higher values were associated with partial and complete tears, these was in agreement with Al Mulla et al. [2], they reported a significant correlation between ADC value and type of lesion that showed increased ADC value in patients with complete or partial AT tear in comparison to patients with inflammation or tendinopathy. Also, Khedr et al. [14] reported that higher-grade pathologies are associated with increased water molecule diffusion**.** In our study, DWI alone showed a good agreement with the gold standard among the studied patients in detecting AT pathologies, with a value that is highly significant (p value <0.001). When adding the ADC value, we reported sensitivity (100%) and specificity (96.67%) in discriminating healthy controls from patients and in discriminating types of AT pathology. Our findings were supported by Aydın et al. [9], who demonstrated that DWI and ADC provided higher sensitivity than routine MRI in detecting Achilles tendon rupture and partial tears. Similarly, Arora et al. [17] & Sharkas et al. [18] & Refaat et al. [19] reported that DWI and ADC mapping improved diagnostic performance in evaluating ligament and tendon injuries. Conversely, Park et al. [20] found no significant diagnostic improvement with the addition of DWI, suggesting some controversy remains regarding its musculoskeletal applications. Only few papers were found covering this subject which led to lack of satisfactory comparison of our results with other studies. The current study has several strengths including its focus on the application of DWI and ADC mapping in Achilles tendon pathologies. The study provided quantitative reference values for ADC in both healthy and pathological AT that provided an objective measure that may reduce reliance on subjective visual

assessment alone. Additionally, the study employed both qualitative and quantitative imaging analyses, increasing diagnostic confidence. Despite promising results, several questions remained. The reproducibility of ADC measurements across different MRI platforms and field strengths needs further investigations. Furthermore, the diagnostic accuracy of DWI in differentiating between overlapping conditions such as inflammation, tendinopathy, and partial tears remains to be fully clarified. Regarding the overall results of the current study, we recommend conducting future multicenter studies with larger sample sizes to validate these findings. Additionally, comparative studies using 3T MRI may provide further insights into the role of higher-resolution diffusion imaging in musculoskeletal applications. Also, future research should evaluate whether DWI can aid in early detection of subclinical tendinopathy, especially in at-risk populations such as athletes or diabetic patients.

CONCLUSIONS

Our study demonstrated that DWI alone contributed limited value, its integration with ADC mapping significantly improved the detection and characterization of Achilles tendon pathology, particularly ADC can distinguish between normal tendons, inflammation, tendinopathy, partial tears, and complete tears. Both techniques showed excellent sensitivity, specificity, and accuracy compared with the gold standard diagnosis. We recommend incorporating DWI and ADC mapping into routine MRI protocols for Achilles tendon evaluation as a complementary tool to conventional imaging, enabling earlier and more accurate diagnosis and guiding better management strategies.

Limitations

This study had several limitations. First, it included a relatively small sample size from a single institution. Second, image quality was limited by the relatively low spatial resolution of DWI sequences. Finally, the study was conducted using a 1.5 Tesla MRI scanner; higher field strength (3T) could potentially improve spatial resolution and diagnostic performance.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Supplementary files

Tables S1& S2 & S3

Author contribution

We acknowledge that all authors have contributed to the model and design, scrutiny and explanation of information, drafting or revising of the manuscript, and that they have permitted the manuscript as submitted.

Conflict of interest

None

Financial disclosure

None

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Table (S1): Site of the injury that detected by DWI among the patients group.

Variables *(n. %)*		Patients group (n=30)
Site	**Non-Insertional**	**19 (63.3%)**
	Insertional	**11 (36.7%)**

Table (S2): Final gold standard diagnosis among the patients group.

Variables *(n. %)*	Gold standard
Normal	**3 (10%)**
Tendinopathy	**10 (33.3%)**
Partial tear	**6 (20%)**
Complete tear	**6 (20%)**
Inflammation	**4 (13.3%)**
Haglund syndrome	**1 (3.3%)**

Table (S3): Diagnostic accuracy of DWI and ADC in detecting total AT pathology

Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)	Accuracy (%)
100%	**75%**	**78%**	**100%**	**95%**

Citation

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