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Beyond Conventional MRI: Added Value of Diffusion-Weighted Imaging in Achilles Tendon Pathologies

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ABSTRACT

Background: Achilles tendon (AT) disorders are common across athletic and general populations and span a spectrum from paratenon inflammation and mid-portion tendinopathy to insertional disease, degeneration, and partial or complete tears. Conventional radiography, CT, ultrasound, and routine MR sequences each contribute valuable anatomical information; however, they are variably sensitive to early micro structural change and may be confounded by artefacts such as the magic-angle effect or the presence of asymptomatic abnormalities. Diffusion-weighted imaging (DWI) offers complementary, functional contrast by probing Brownian motion of water within intra- and extra-cellular spaces, with qualitative (high-b signal) and quantitative (apparent diffusion coefficient, ADC) readouts that reflect tissue organization, cellularity, and fluid content. In the Achilles tendonan anisotropic, collagen-rich structure with regional hypovascularity DWI has the potential to improve lesion conspicuity, characterize tendinopathy phenotypes, differentiate degeneration from tears, and monitor treatment response. This review synthesizes anatomical, biomechanical, and microstructural substrates relevant to DWI interpretation; contrasts DWI with conventional MRI, ultrasound, and other advanced techniques; and collates emerging evidence on the qualitative and quantitative value of DWI and ADC mapping in AT-related pathologies. We discuss technical considerations unique to musculoskeletal DWI for integrating DWI into routine ankle MRI protocols. Collectively, current data support DWI as an adjunct that augments diagnostic confidence beyond conventional MRI, particularly in distinguishing fluid-rich inflammatory processes from collagen-dense degenerative change.

Keywords*: Conventional MRI, Diffusion-Weighted, Achilles Tendon Pathologies*

INTRODUCTION

The Achilles tendon (AT) is the largest and strongest tendon in the human body **[1].** It is formed by the merging of the gastrocnemius and soleus tendons and inserts at the calcaneal tuberosity **[2].** Despite its size and strength, the AT is vulnerable to acute ruptures and chronic overuse pathologies, largely due to its unique anatomical, vascular, and biomechanical features **[3].**

MRI, with its multi-planar imaging modality which performs high-resolution images **[4].** The use of new MRI sequences enables the early identification and differentiation between the types of tendinopathy **[5].** In the enthesopathies, the degree of bursitis, the presence of tendon changes, and the presence of bone marrow edema in the bony insertion can be determined on MRI, Some surgeons prefer having MRI imaging to study the extent of the disease and visualize the surrounding tissues for operative planning **[2].** However, conventional MRI is sometimes limited by pitfalls such as magic angle artifact that plays an important role in imaging of the ankle because of the course taken by the tendons toward their insertion onto the foot **[6].**

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Diffusion-weighted imaging (DWI), a functional MRI technique based on the Brownian motion of water molecules, has emerged as a promising adjunct to conventional musculoskeletal imaging **[7].** DWI provides quantitative measurement of the motion of water molecules at the pathological and normal tissues, net diffusion of water molecules is known as the ADC, and it combines the effects of capillary perfusion and water diffusion in the extracellular space In the Achilles tendon, DWI theoretically might supplement relevant data beneath the routine MRI, via presenting the motion and diffusion of water molecules through the diseased tendons, showing the accumulated effusion within the tendon sheath plus peritendinous areas, and supplying a good-contrast between the injured tendons and normal surrounding soft tissue **8].**

The aim of this review is to critically evaluate the added value of qualitative and quantitative DWI in Achilles tendon pathologies beyond conventional MRI. We summarize relevant tendon anatomy and microstructure, outline the principles and technical considerations of DWI and discuss its role in differentiating the spectrum of AT disorders.

By doing so, we aim to provide radiologists and musculoskeletal clinicians with a comprehensive understanding of how DWI can enhance the diagnostic and clinical management of Achilles tendon pathology.

Anatomy:

The Achilles tendon is a unique anatomical structure formed by the confluence of the medial and lateral gastrocnemius and the soleus tendons, extending approximately 15 cm in length with an average thickness of 6 mm **[1].** During its descent, the tendon fibers undergo a spiral rotation of nearly 90°, degrees laterally during its course to insert on the posterior aspect of the calcaneal tuberosity **[2].**The fibres of the Achilles tendon internally rotate 90 degrees in a spiral manner as they descend, an arrangement that optimizes elastic energy storage and recoil during locomotion **[3].**

The AT is composed of three rotating sub-tendons originating from the three parts of the triceps surae muscle: the medial head of the gastrocnemius (MG), the lateral head of the gastrocnemius (LG), and the soleus muscle (SOL). These sub-tendons descend, rotating laterally to their insertion point, the calcaneal tuberosity **(Figure 1) [9].**

The lateral and medial bellies of the gastrocnemius muscle join the deeper soleus muscle in an aponeurosis approximately 12–15 cm from the insertion of the tendon into the calcaneus The two tendinous components of the gastrocnemius and the soleus muscles fuse to become one solo tendon about 5–6 cm proximal to the calcaneal insertion **[1].**

Tendon's related bursa:

There are two bursa located at the posterior heel which function to lubricate and protect the Achilles tendon by reducing friction between the tendon and adjacent tissues **[10] (Figure 2).** A subcutaneous superficial calcaneal bursa permits movement of the skin over the flexed tendon. A deep bursa of the Achilles tendon called retro-calcaneal bursa reduces friction to allow free movement of the tendon over the bone **[11].** The retro-calcaneal bursa is horseshoe shaped and has two arms that extend medially and laterally on either edge of the tendon. It largely consists of highly mobile synovial projections that undergo shape alterations throughout the range of motion of the ankle **[10].,** its function is to reduce friction associated with the tendon's movement in surrounding tissues. **[12].**

The enthesis of the AT, described as the “enthesis organ,” is the site at which the Achilles tendon inserts at the calcaneous. This complex includes the calcaneal fibrocartilage, sesamoid fibrocartilage, retrocalcaneal bursa, and Kager’s fat pad, which together act to dissipate large torques generated during locomotion **[13].**

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Microstructure, Vascularity, and Neural Elements.

The Achilles tendon is primarily composed of type I collagen fibrils embedded within a proteoglycan-rich extracellular matrix, interspersed with tenocytes and tenoblasts arranged in longitudinal rows These tightly packed fibrils form bundles that are further organized into fascicles surrounded by the endotenon, while the epitenon and paratenon envelop the tendon externally **[3].** A normal ligament (rich in collagen and very poor in water) shows hypo intense signal on ADC mapping. But in cases of tendon pathology an abnormal hyper intense signal corresponding to the fluid infiltration induced by traumatic tear of the ligament **[14].**

-The Achilles tendon has its blood supply from longitudinal arteries which course the length of the tendon from two main blood vessels **[15]:**

1. Posterior tibial artery: Which supplies the proximal and distal sections.
2. Peroneal artery: Which supply the middle section.

The tendon has a generally poor blood supply throughout its length, as measured by the number of vessels per cross-sectional area. In addition, a relative region of hypo vascularity exists in its midsection which usually happens to be the site around which most injuries occur. This has been attributed as a contributing factor to diminished healing after trauma **[16].**

Neural innervation of the Achilles tendon also plays an important role in its pathology. It is supplied by branches from the tibial and sural nerves, with a network of free nerve endings and mechanoreceptors distributed predominantly near the osteotendinous junction **[10].** These include Ruffini and Pacinian corpuscles as well as Golgi tendon organs, which contribute to proprioception and nociception **[17].**

Conventional Imaging Modalities:

X-ray imaging technique is the most widely available and the cheapest imaging modality that used in the imaging of the acute ankle injury as it helps at detecting of bone fractures, giving a clue about a tendon injury, foreign body detection **[18].**

Computed tomography excels at bony detail and calcification but lacks functional or soft-tissue evaluation **[19].**

Ultrasound (US) is a highly sensitive and commonly used tool for diagnostic assessments of tendons and entheseal site. Due to the superficial position of the Achilles tendon US is used to assess the Achilles tendon. It can detect tendon thickening, enthesophytes, and erosions and also demonstrates tendon swelling and thickening, discontinuity of tendon fibers, focal hypoechoic intratendinous areas, and fluid around the tendon, pitfall in diagnostic US can be the artifacts such as anisotropy that happens when tissues show abnormal echogenicity, most commonly loss of echogenicity, due to an oblique insonating angle. Tendons or ligaments may appear as hypoechoic and thus could be misinterpreted as tendinosis or tears **[20].** .

MRI is a multi-planar imaging modality which performs high-resolution images **[4]**, allows the assessment of Achilles tendon pathologies including tendinopathy, enthesopathies, tears, bursitis, and associated bone marrow or soft tissue changes in surroundings **[2].** However, conventional MRI is sometimes limited by pitfalls such as magic angle artifact that plays an important role in imaging of the ankle because of the course taken by the tendons toward their insertion onto the foot **[6].**

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Normal Achilles tendon at MRI.

A normal Achilles tendon appears hypo-intense (dark) on all MRI sequences because of its very low water content. It appears long and thin on sagittal cuts, and round, uniform, and well-defined on coronal images. On sagittal images, the anterior and posterior margins of the Achilles tendon should be parallel below the soleus insertion . On axial images, the anterior margin of the Achilles is concave for most of its course. Somewhat proximally, just above the soleus insertion, the margin may be straight or convex; at the soleus insertion, the margin is typically convex and may be focally bulbous. On coronal images, both sides of the Achilles are fairly straight and the tendon widens as it extends distally at the lesion. The normal retrocalcaneal bursa is visible on MR imaging but should measure less than 6 mm superior to inferior, 3 mm medial to lateral, and 2 mm anterior to posterior **[21] (figure 3).**

Achilles tendon injury

The Achilles tendon injury range from tendinosis, partial tears to complete tear **[22].**

--*Achilles tendinopathy (Figure 4):*

tendinopathy can be broadly divided into insertional and non-insertional Achilles tendinopathy **[10].**

-Insertional tendonopathy: Focal tendinopathy that occurs near the calcaneus is usually aresult one of three causes: sero-negative arthropathy, retro calcaneal bursitis, or chronic traction injury **[23].**

- Non-insertional tendinopathy: occurs 2 to 6 cm proximal to its insertion. There is typically no calcaneal spur, and the pathology is primarily intratendinous **[24].** This is usually associated to micro ruptures when overuse mechanisms are present. The presence of this type of disease is less common at the myotendinous junction, which is more related to muscle tearing phenomena **[25].**

***DEGENERATION**:*

Tendinosis is a degenerative, non-inflammatory process, most closely associated with aging **[26].**

-Fibromatous degeneration “hypoxic degenerative tendinopathy”:

It is the most frequently seen degenerative finding in ruptured Achilles tendons ,these hypoxic changes are likely caused by ischemia because of the relative hypovascularity of the critical zone of the Achilles tendon, this hypo vascularity results in anoxic injury to tenocytes and collagen fibers. Hypoxic degenerative tendinopathy leads to a thickened dysmorphic Achilles tendon, this type of degeneration usually occurs after multiple symptomatic episodes and usually lacks internal signal on MR imaging **[27].**

-Mucoid degeneration:

In mucoid degeneration, large mucoid patches and vacuoles are seen between the thinned degenerated tendon fibers Interrupted signal on T2-weighted images is the best marker for mucoid deposits . Grossly, these tendons appear enlarged, and enlargement may also be seen on MR imaging. It is the coalescence of vacuoles and lacunae that is the beginning of an interstitial tear. Patients with mucoid degeneration may have a tear at first clinical presentation because earlier episodes were asymptomatic **[27].**.

A typical presentation of tendinosis is the middle-aged athlete who presents following an increase in training duration, intensity, and frequency with pain in the mid portion of the tendon. On physical examination, the patient presents with swelling after activity and pain with active and passive

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motion.Visible or palpable tendon enlargement or a knot, which is painful are common findings **[28].** With MRI, there is tendon enlargement without internal signal changes .Mucoid degeneration leads to enlargement with altered T2-weighted signal, reflecting mucoid deposits and interstitial tears **[29]**. Interstitial tears present as longitudinally oriented linear increased signal on T1-weighted, proton-density-weighted, and T2-weighted and STIR sequences, with intact surrounding fibers **[30], [27].**

Tendon Achilles tears:

Despite its size and tensile strength, Achilles tendon is the most commonly injured tendon in the human body **[31].** In general, 2 things are necessary in order for a person to rupture his or her Achilles tendon. One is tendinosis. The second is an eccentric contracture of the muscle-tendon unit of sufficient force that the tendon mechanically fails. Most patients have no symptoms whatsoever prior to rupture **[32].**

Most tears occur in the less vascularized zone of the Achilles tendon, located 2–6 cm from its calcaneal insertion **[23].** Rupture may be partial, complete and intra substance. Complete rupture is the most common presentation **[33],** almost all tears show high signal on T2-weighted imaging **[23].** Interstitial tears typically show a longitudinal orientation and are thought to result from myxoid degeneration. Partial-thickness tears show disruption of tendon fibers with heterogeneous signal between the fibers. Retraction of tendon fibers with buckling may be present, but some fibers remain intact. Full-thickness tears involve all fibers, with a fluid-filled gap at the injury site and the tendon fibers either retracted or overlapping. Over time, the hematoma between the tendon ends resolves, and granulation and scar tissue form **[23]**.

On MRI, partial tears demonstrate alteration in architecture with interruption of tendon fibers. Heterogeneous T2 hyper intense signal fills the tendon defect and outlines the ends of the torn fibers, which can partially retract **[30] (figure 5).** Complete tears of the Achilles tendon results in tendon discontinuity with fluid or heterogeneous signal hematoma filling the tendon gap, and torn tendon fibers are distracted or overlapping **[30]**. Peritendinous hemorrhage and edema are present with recent tendon tears. As the tear ages, organization of the hematoma, granulation tissue, and eventual scar tissue can make detection of the torn tendon edges difficult **[1].**Chronic ruptures often demonstrate muscle atrophy with further retraction of the tendon **[1].**

Principles of Diffusion-Weighted Imaging and ADC Mapping

Diffusion-weighted magnetic resonance imaging (DWI) is a new addition to the musculoskeletal MR sequences being used at many institutions. The signal intensity of DWI relies on the stochastic Brownian motion, or self-diffusion, of water molecules at a microscopic level within tissues. Extracellular water is more freely mobile, in comparison to intracellular water molecules that show limitations in their motion by intracellular organelles, macromolecules and cell membranes. Water molecular diffusion on clinically acquired DWI sequences is therefore reflective of tissue organizational features, principally cellularity (number of cells per high power field). Areas with higher cellularity will show impeded molecular water mobility to a greater extent than areas where there has been loss of cellular integrity, such as areas of necrosis or injury. DWI can therefore add functional information obtained at the cellular level to aid in the differentiation of normal and pathological tissues **[7].** A diffusion weighted image is created by applying diffusion sensitizing gradients to a T2-weighted image, where the parameters of the sensitizing gradient are determined by the b value. With a b value of 0, the image appears as a T2-weighted image and a progressive increase in the b value begins to

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suppress the perfusion effect, with only highly cellular tissues remaining bright at high b values. A hyper intense signal on DWI corresponds to an area where water motion is restricted and is not able to move out of the image plane **[34].** DWI allows quantitative measurement of the motion of water molecules into the lesions and normal tissues. ADC is the net diffusion of water molecules, and it combines the effects of capillary perfusion and water diffusion in the extracellular space **[8].** DWI qualitatively has been shown to have the potential to facilitate the detection of structural and biochemical changes in tissue, while the quantitative ADC measurements provide early diagnostic indicators of the presence of pathological changes and of monitoring tissue damage **[35].** ADC mapping with b-values from 0 to 1000 s/mm2 can be performed and it has been shown to be more sensitive than DWI, as it is influenced only by the magnitude of the diffused water molecules **[8].** DWI has been widely used for the detection of perfusion deficiencies in the brain, resulting in cerebral ischemia, but over the last few years, extracranial applications of DWI have been performed for the evaluation of abdominal organ pathologies, especially for the differentiation between benign and malignant lesions of the liver and kidneys, head and neck disorders, and assessment of lymphadenopathies throughout the whole body **[8].**

DWI is increasingly becoming popular in musculoskeletal radiology for its incremental role in the diagnostic strategy and assessment of therapeutic response of bone and soft tissue lesions. Its ability to differentiate tissues and lesions at different diffusion speeds enhances the capability of conventional MRI to more functional evaluation, allowing radiologists to render better and more confident diagnostic assessments **[36].**

Tissue rich in free water (interstitial or intra-articular fluid or infiltrated between damaged tissue) has a high diffusion coefficient (hyper intense signal in ADC mapping). Inversely, tissue containing bound water (e.g. the cytotoxic cell edema observed in arterial vascular accidents) has a reduced diffusion coefficient and tissue containing very little water (bone, fat, and ligament tissue rich in collagen) has none at all. A ligament fragment (rich in collagen and very poor in water) has a hypo intense signal on ADC mapping. It is surrounded by a hyper intense signal corresponding to the fluid infiltration induced by traumatic tear of the ligament and its surrounding tissue. So,edema or fluid infiltration yields high ADC, whereas fibrotic or collagen-rich tissue shows low ADC **[14].**

Role of DWI and ADC in Achilles Tendon Pathology

Injuries of the Achilles tendon commonly exhibit a combination of underlying pathologies. Therefore, appropriate imaging evaluation and diagnosis are cardinal to guiding appropriate management **[23].**There is difficulty in differentiating AT partial and complete tears by using routine MRI. However, certain features such as wavy ligaments or ligament thinning are suggestive of partial tears, but, determination of partial tears still remains a challenge **[34].** This difficulty can be attributed to the edema that results from the injury, which appears as a hyper intense signal on T2-weighted images, obscuring ligament fibers. DWI might supplement relevant data beneath the routine MRI, via presenting the motion and diffusion of water molecules through the diseased tendons, showing the accumulated effusion within the tendon sheath plus peritendinous areas, and supplying a good-contrast between the injured tendons and the surrounding normal soft tissue. These contrast differences in the imaging approaches, revealing the diseased tendons, probably supply the most important data for clinical practices **[8].** However, it was found that applying DWI to tendon traumatic injuries can aide in the differentiation between partial and complete tears and that ADC mapping may be more useful in differentiating partial and complete tears than morphological MRI alone **[14].** Aydın et al.; 2022,

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stated that DWI had 100% sensitivity and 83–90% specificity for the visualization of tendon injuries with certain agreement and a significant statistical relationship to MRI, and also concluded that DWI was superior to ankle MRI for the evaluation of rupture, partial tears, and tenosynovitis of all studied tendons. But they reported that DWI was more sensitive than MRI for the detection of AT rupture without any statistical superiority. They found that DWI had 100% sensitivity for the diagnosis of rupture and 92–97% sensitivity corresponding to partial tears and tenosynovitis over routine ankle MRI **[8].** Al Mulla et al., 2019, found a significant correlation between ADC value and type of lesions indicated that ADC values were statistically significant when differentiating type of AT pathology **[35].** They showed that an increased ADC is evident in patients presenting with AT complete, partial and, micro tears in comparison to patients with AT thickness, inflammation or tendinopathy. This finding may be attributed to the increased diffusion of water molecules associated with high-grade pathology compared to lower grade pathology **[37].** As mentioned before, DWI & ADC are based on the diffusion of free water in tissue. Therefore, tissues rich in free water have a high diffusion coefficient and give a hyper intense signal on ADC mapping **[37].** While, ligament fragments have abundant collagen and little water which appears hypo intense on ADC mapping. Ligament fibers have been shown to be better visualized on ADC mapping and therefore, ADC mapping may be able to verify if the ligament is continuous or not **[14].** McNish et al. 2024 suggested that quantitative MRI is reliable to assess the Achilles tendon lesion. It can assess the presence of tendon pathology and relates to functional performance outcome, and they supported the utility of incorporating it in research field and clinic **[39].**

Combination of DWI and ADC mapping to conventional MRI improved the overall sensitivity and specificity in detection of AT pathology **[35].**

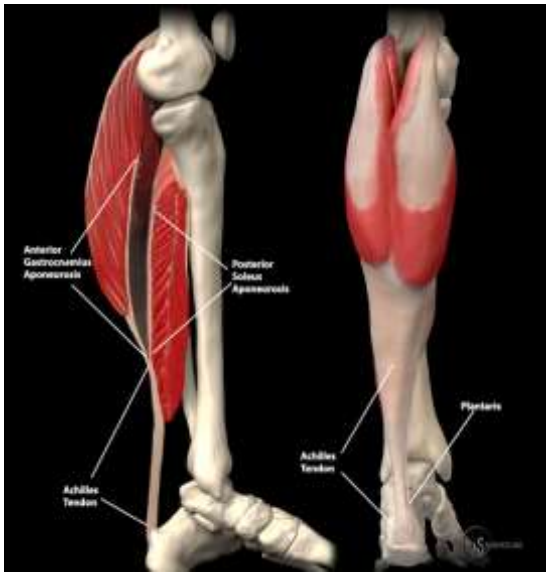

Figure 1: The Achilles tendon forms from the aponeuroses of the gastrocnemius and soleus muscles. The plantaris tendon extends to the medial surface just proximal to the level of fusion and extends distally to its insertion **[40].**

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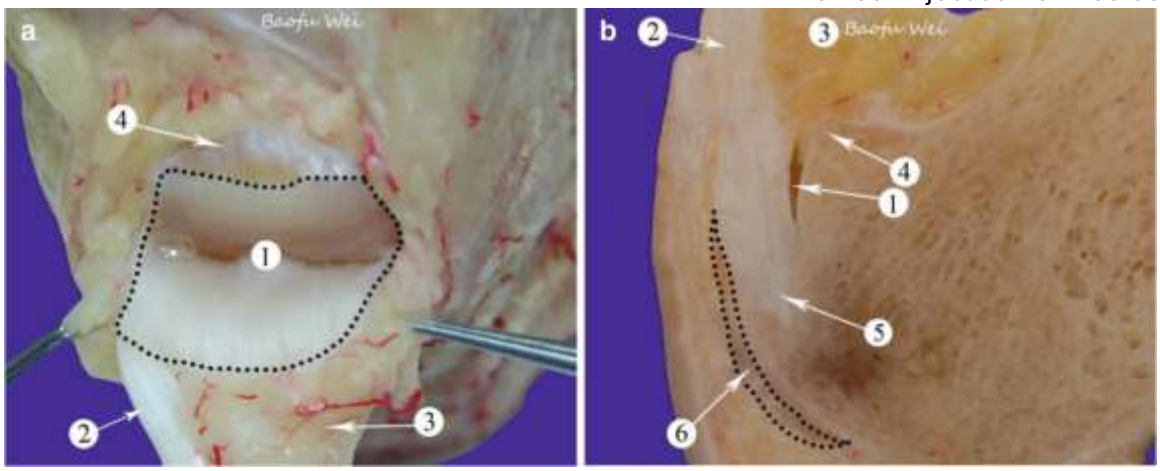

Figure 2: The gross anatomy of the retrocalcaneal bursa. (a) The gross anatomy of the retrocalcaneal bursa. (b) Sagittal view of the retrocalcaneal bursa. (1) Retrocalcaneal bursa. (2) Achilles tendon. (3) Fat tissue. (4) Posterior superior tubercle of calcaneus. (5) Insertion of Achilles tendon. (6) Subcutaneous calcaneal bursa **[10].**

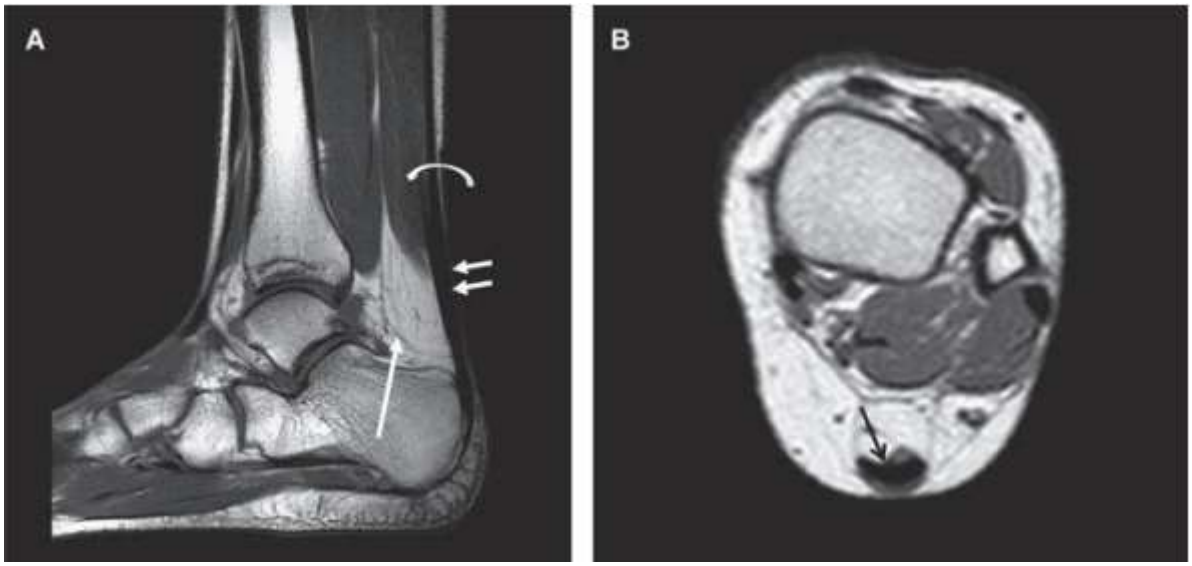

Figure 3: A. MR T1W sagittal image of the Achilles tendon. The normal tendon has low signal intensity from proximal to distal with parallel margins below the soleus insertion (short arrows). The tendon contrasts with the soleus muscle (curved arrow) and the Kager's fat (long arrow). B. MR T1W axial image of the Achilles tendon. In axial plane, the anterior margin of the normal tendon has a concave appearance (long arrow) **[1].**

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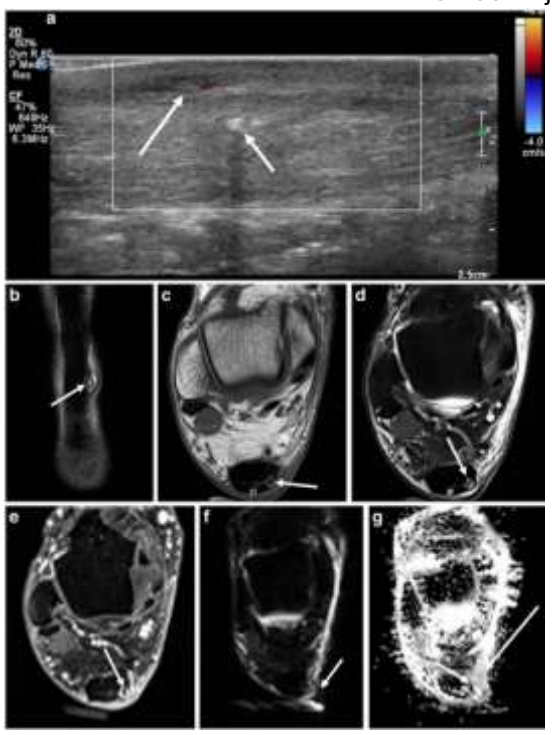

Figure 4: Cellulitis, tendinitis and gas (arrows). US (a), sagittal fsT2W (b), axial T1W (c), fsT2W (d), post-contrast fsT1W (e), DWI (f) and ADC (g) images of an adult man with local injury over posterior lower calf and suspected infection. Notice increased Doppler flow on US (large arrow in a) and restricted diffusion (ADC value of 1.6 × 10−3 mm2 /s (large arrow in g). Achilles tendon infection site shows target sign due to intratendinous air (small arrows in b –g), which causes local distortion of DWI (arrow in f) **[41].**

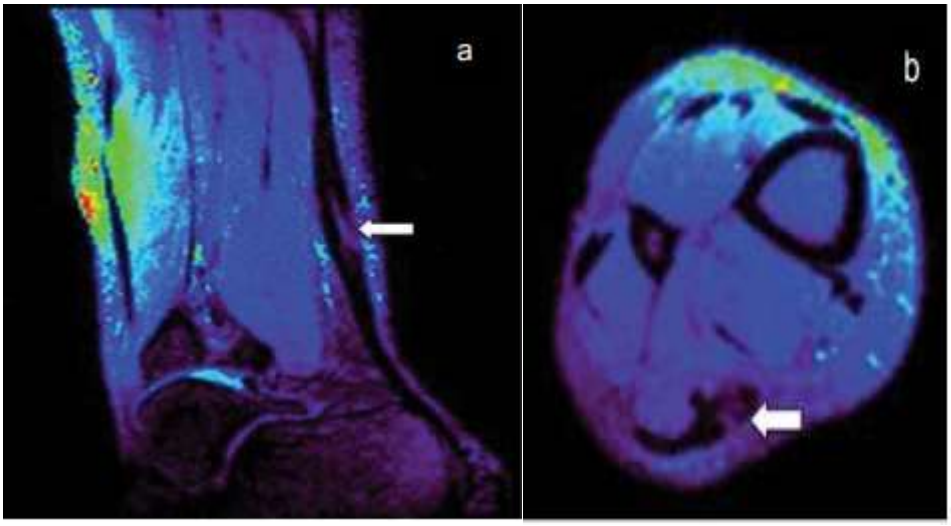

Figure 5: Sagittal (a) Axial; (b) Images of abnormal AT using a DW sequence based on SSFP technique. Both images demonstrate high image resolution regarding differentiating AT hypo intense signal relative surrounding anatomy, with an increase in signal shown where a abnormally (tear) within the tendon (arrow) **[35].**

Conclusion

Diffusion-weighted imaging (DWI) and apparent diffusion coefficient (ADC) mapping offer meaningful advances in the evaluation of Achilles tendon disorders. While conventional MRI remains

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the cornerstone for structural assessment, DWI adds functional insight into tissue micro architecture and water mobility, enabling more precise differentiation among tendinopathy, degeneration, partial or complete tears, and postoperative or infectious conditions. Qualitative DWI highlights areas of abnormal diffusion, and quantitative ADC provides objective biomarkers to support diagnosis, monitor disease activity, and help predict recovery. Despite current limitations—technical artifacts, variable acquisition protocols, and the absence of standardized ADC reference values—continued research and technical refinement are likely to enhance its clinical role. In summary, DWI and ADC mapping provide complementary functional information beyond conventional MRI, improving diagnostic confidence, guiding individualized treatment, and offering a promising tool for longitudinal monitoring of Achilles tendon health.

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