SONOGRAPHY

EDUCATION ARTICLE

Ultrasound of flexor digitorum apparatus in acute and chronic pathology

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Abstract

The flexor digitorum apparatus (FDA) of the finger consists of two flexor tendons located within their osteofibrous tunnel, reinforced by the pulley apparatus and the supporting volar plates. The FDA is essential for facilitating hand grasping functions, and pathology affecting the FDA can result in functional impairment of the hand. These injuries can be open or closed in nature and are commonly the sequelae of acute trauma or chronic overuse. This article includes an overview of the anatomy of the FDA, ultrasound scanning technique and common pathologies that sonographic assessment may encounter. The anatomy of the finger and its variants is complex, and an ultrasound can only be accurate if the operator possesses comprehensive knowledge of these structures.

Introduction

Pathology affecting the flexor digitorum apparatus (FDA) requires early diagnosis and timely treatment to avoid functional impairment of the hand.[1] These conditions are often associated with acute injuries or chronic micro-trauma.[2] With recent advances in high frequency transducer technology, providing improved superficial structure resolution, the FDA can be assessed with great confidence. Ultrasound can depict partial or complete tendon tears from the myotendinous origin to their osseous insertion. Dynamic ultrasound, with passive or active joint movements, adds sensitivity and specificity in the diagnosis of the condition.[3] The efficacy of ultrasound findings enables the physician to choose between surgical and conservative treatment options.[4] This article reviews the anatomy and function of the FDA, outlines the ultrasound technique and discusses the ultrasound features of common disorders affecting the FDA.

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Anatomy and function of the flexor digitorum apparatus

Each of the four digits has two flexor tendons: the flexor digitorum superficialis (FDS) and the flexor digitorum profundus (FDP). In the palm, the FDS lies superficial to the FDP. At the level of the proximal third of the proximal phalanx the FDS divides, the two slips separating to the radial and ulnar aspects allowing the FDP tendon to pass between the slips. FDS divides into two slips passing ulnar and radial the FDP. As they pass posteriorly, they wrap around FDP with the inner fibres of each slip crossing over to the contralateral side forming the insertional slips, which continue distally, inserting onto the proximal half of the middle phalanx. At the point where the FDS slips intersect posterior to FDP, there is a connection of fibres that forms the Camper chiasm (Figure 1).[5]

The primary function of the FDS is to flex the proximal interphalangeal (PIP) joint and assists with metacarpophalangeal (MCP) flexion. The FDP passes through the divided FDS to insert at the base of the distal phalanx where its primary function is to flex the distal interphalangeal (DIP) joint.

At the level of the metacarpal head, the tendons enter an osteofibrous tunnel, which is made of five thick

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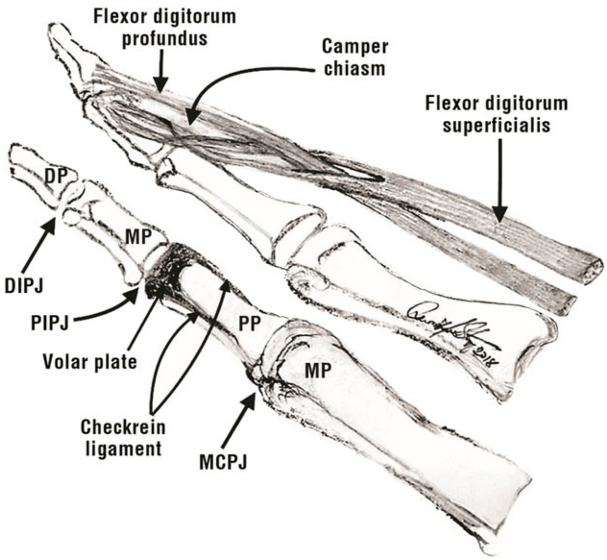

Figure 1 Flexor system of the finger. DIPJ, distal interphalangeal joint; DP, distal phalanx; MCPJ, metacarpophalangeal joint; MP, mid-phalanx, PIPJ, proximal interphalangeal joint; PP, proximal phalanx.

arciform annular pulleys and three thin crisscrossing cruciate pulleys that are numbered in ascending order from proximal to distal (Figure 2). The A1, A3 and A5 pulleys are located over the MCP, PIP and DIP joints, respectively. The A1, A3 and A5 pulleys are narrow, flexible and insert mostly into the volar plates.[6,7] The A2 and A4 pulleys are wider and insert directly into the bone over the proximal and middle phalanges, respectively. The annular pulleys are made of concentric collagen fibres that can resist loads of up to 700 N.[8,9] The cruciate pulleys of C1, C2 and C3 lie between the A2–A3, A3–A4 and A4–A5 annular pulleys, respectively. The major function of the pulley system is to stabilise and prevent volar bowstringing of the flexor tendons during finger flexion.[6,7] The A2 pulley is the strongest and is the primary restraint to bowstringing of the flexor tendons during finger flexion under load.[6,7,10,11] Bowstringing displacement of the flexor tendons will diminish their mechanical efficiency and compromise flexion strength.[4]

There are three volar plates located at the MCP, PIP and DIP joints (Figure 3). They are multilayered condensation of fibrocartilaginous tissue, which form the floor of the respective joints. They behave like a meniscus between the metacarpal/phalangeal head and the adjacent phalangeal base. The volar plates are thicker at their distal phalangeal attachment and thinner at the proximal origin. Functionally, the volar plates prevent hyperextension, lateral displacement and torsional forces that act on the joints. They also act as a smooth gliding interface for the flexor tendons.[12] At the PIP joint volar plate proximal origin, checkrein ligaments form thin extensions on either side and merge with the volar periosteum of the proximal phalanx.[13] The volar plate acquires its vascular supply from the proximal transverse palmer arch, which has a 'horseshoe' pattern, supplying the proximal portion of the volar plate.[14]

Ultrasound technique and ultrasound anatomy of the flexor digitorum apparatus

The normal anatomy of the finger and its anatomical variants is complex. Knowledge of the anatomy is essential to the accurate performance of diagnostic ultrasound. Obtaining a precise patient history, review of other imaging and performance of a basic clinical examination are essential in forming the correct

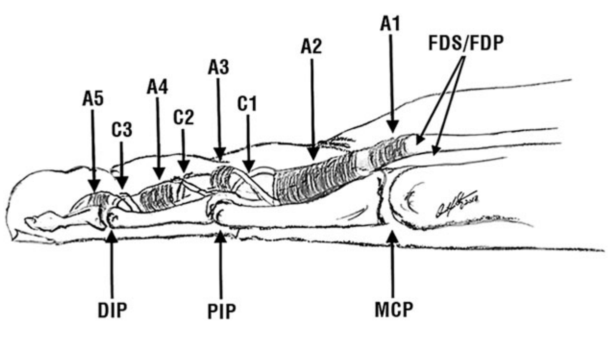

Figure 2 Annular and cruciate pulleys system. DIP, distal interphalangeal; FDP, flexor digitorum profundus; FDS, flexor digitorum superficialis; MCP, metacarpophalangeal; PIP, proximal interphalangeal.

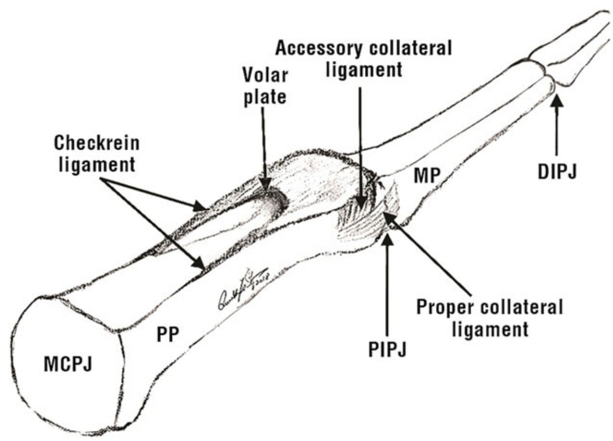

Figure 3 The volar plates at the proximal interphalangeal joint. DIPJ, distal interphalangeal joint; MCPJ, metacarpophalangeal joint; MP, mid-phalanx; PIPJ, proximal interphalangeal joint; PP, proximal phalanx.

diagnosis. Transducers operating in the 10- to 24-MHz range should be utilised to produce high-quality images of the superficial structures. A compact linear (hockey stick) transducer, with a small footprint, enables ease of manoeuvering and dynamic assessment during movement of joints and tendons. Colour Doppler is essential to detect internal vascularity and signs of inflammatory change. Comparison with adjacent fingers or the other hand is very helpful for determining subtle pathology changes.

Sonographic examination of the FDA begins in the palm scanning short axis to the tendons at the level of mid-metacarpal bones. As the transducer moves distally, the superficially located FDS tendon can be seen dividing on either side of the FDP tendon before reforming deep to the FDP tendon and inserting into the proximal half of the middle phalanx. The FDP tendon continues distally inserting onto the base of the distal phalanx. Assess the FDA in the longitudinal plane utilising a dynamic scanning manoeuver, to differentiate between FDS and FDP. With the finger in an extended position stabilise the PIP joint while passively flexing and extending the DIP joint allowing the FDP tendon to slide under a stationary FDS tendon at the level of the MCP joint. Gliding of both flexor tendons can be evaluated by concomitant flexion and extension of the PIP and DIP joints. Normal tendons will demonstrate a characteristic hyperechoic fibrillar pattern immediately superficial to the metacarpal, phalanges and underlying joints.[7] The synovial sheath enveloping the tendons appears as a thin membrane, which may be difficult to visualise in normal patients.[4]

Placing the transducer over the MCP joint in long axis (LAX), the A1 annular pulley appears as a thin hypoechoic band immediately anterior to the flexor tendons. Following the tendon distally will demonstrate the remaining annular pulleys in ascending order. In short axis, the normal annular pulleys appear as thin curved hypoechoic bands covering the flexor tendons. The diverging lateral aspect of the annular pulleys appears hypoechoic as a result of anisotropy. Dynamic scanning in LAX with passive and active movement of the finger sees the flexor tendons gliding beneath the pulleys. The normal cruciform pulleys are not usually visible on ultrasound.

Assessment of the volar plate is performed by placing the transducer in LAX over the volar aspect of the MCP joint or interphalangeal joints. The plate appears as an echogenic, homogeneous structure underlying the flexor tendons bridging the joint. Active hyperextension of the finger will see an intact volar plate following the movement of the phalanx base.

Flexor tendons – Open or closed injuries

Open injuries – Laceration to flexor digitorum superficialis and flexor digitorum profundus tendons

Injuries to flexor tendons are categorised as either open or closed injuries. Open injuries are the consequence of lacerations and penetrating trauma in which the soft tissues overlying the flexor tendons are disrupted. Closed injuries occur when the overlying soft tissues are intact, usually as a result of acute trauma from sport or manual work.[9] Rarely closed flexor tendon rupture may be caused by rheumatoid arthritis, gout or other arthropathies.[15]

Traumatic finger injuries are common, accounting for approximately 20% of patients presenting to the emergency department.[16] Injuries range from superficial lacerations to more serious injuries involving penetration of the tendon(s). Approximately 1–2% involves tendon laceration most commonly on the volar aspect.[1] The laceration may be partial or complete and may involve only the FDS or FDP tendons or both (Figure 2). The trauma may be associated with vascular injuries or nerve damage.[8] As many as 5% of hand injuries need surgical intervention making timely diagnosis important for appropriate management. Hand trauma is often complicated by the complexity and intricacy of the anatomy.[15] The role of ultrasound with traumatic finger injuries is to aid the treatment, enabling the physician to choose between surgical exploration and conservative treatment.

Kleinert *et al*.[17]and Verdan[18] classified tendon injuries into five anatomic zones:

- Zone I extends from the insertion of the FDS to the insertion of the FDP.
- Zone II extends from the A1 pulley to the distal insertion of the FDS.
- Zone III extends from the distal flexor retinaculum of the carpal tunnel to the proximal part of the A1 pulley and contains the lumbrical origins from the FDP tendons.
- Zone IV is composed of the flexor tendons within the carpal tunnel.
- Zone V is composed of the forearm proximal to the carpal tunnel.

Zone I laceration will result in loss of DIP flexion caused by injury to the FDP tendon. Laceration occurring in zones II–V will result in loss of both DIP and PIP joint flexion as they involve injuries to both FDP and FDS.[16] Lacerations in zone II are the most common, usually affecting the mid-substance of the tendon rather than the distal insertion.[15] Zone II injuries have the most pessimistic prognosis because of the frequency of complications including adhesions, entrapment or triggering of the flexor tendons from scar formation under the A2 pulley. When an injury to zone II occurs early surgical exploration is often required to avoid functional impairment of the hand.[15,16] Ultrasound is able to differentiate between partial and complete laceration defining the extent of the laceration utilising LAX imaging and axial imaging for confirmation. Axial plane imaging allows easy differentiation between FDS and FDP tendons (Figure 4).

Closed trauma injuries of the flexor tendons

The most common closed trauma rupture of the FDA is failure of the distal insertion of FDP and is known as a *jersey finger injury*. Clinically, the patient reports sudden pain, at the time of injury followed by the inability to flex the DIP joint. This type of rupture is commonly due to sudden hyperextension of the DIP joint during active flexion.[19] Seventy-five per cent of the cases involves the ring finger.[20] Sonographically, the affected finger shows retraction of the FDP tendon with an anechoic or blood-filled space, which once housed the FDP tendon (Figure 5). For management decision-making and prognosis prediction, Leddy[20] classify these injuries into three types:

- Type I results in FDP tendon retraction into the palm resulting in significant loss of blood supply to the tendon.
- Type II results in FDP tendon retraction to the PIP level with partial loss of blood supply to the tendon.
- Type III injuries involve a large avulsion fracture of the base of the distal phalanx, which limits FDP retraction to the level of the DIP because of the bone fragment being tethered at the A5 pulley.[20]

Other experts added three additional types:

- Type IV occurs when there is a large avulsion fracture of the base of the distal phalanx, but the bone fragment is not attached to the FDP tendon, which retracts into the palm.[21]
- Type V involves avulsion of the FDP associated with a separate fracture of the distal phalanx.[22]
- Type VI 'false mallet finger' is described as the insertion of the FDP, remaining intact but the dorsal aspect of the distal phalanx is fractured (Figure 6).[9]

Flexor tendon ruptures result in a greater degree in retraction compared with extensor tendon ruptures as the extensor system anatomy is imbedded with robust connection fibres preventing retraction.[16]

Physical examination of flexor tendon rupture from either open or closed injuries can be difficult and requires significant clinical experience.[3] In a study of 147 deep lacerations of the hand, with surgically confirmed complete tendon tears, only 64% were diagnosed successfully by emergency physicians and 84% by hand surgeons.[23] The limited reliability of physical examination even by hand surgeons has resulted in widespread use of surgical exploration whenever a deep lesion is suspected.[3] In the same study of 147 injuries, hand surgeons mistakenly diagnosed 10 tendon tears and 17 nerve injuries, which were shown to be falsely positives at surgical

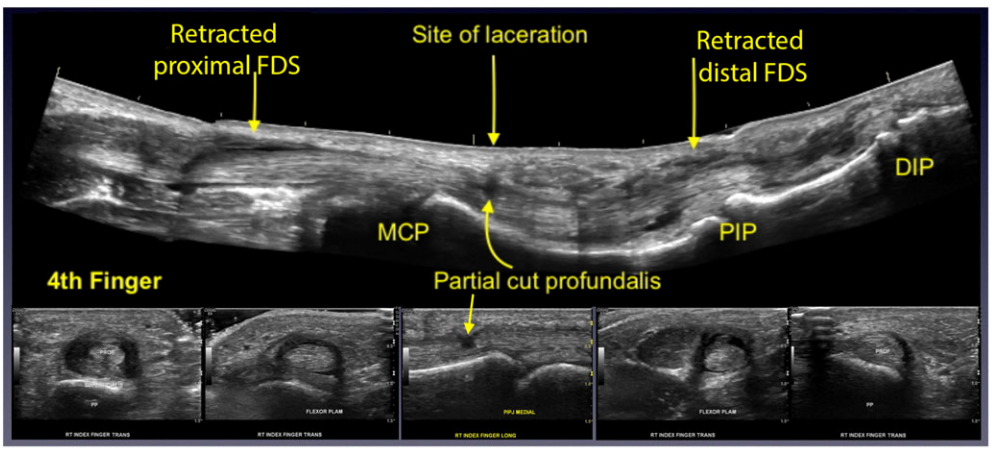

Figure 4 Open injury of the flexor tendons. Panoramic ultrasound demonstrates a complete rupture of flexor digitorum superficialis (FDS) and partial tear of flexor digitorum profundus. The site of laceration is at the level of the proximal one-third of zone II. The FDS proximal fragment is retracted to the level of the mid-metacarpal; the distal fragment of the FDS is retracted to the level of proximal interphalangeal (PIP) joint. The short axis view shows the corresponding level of the flexor tendons. DIP, distal interphalangeal; MCP, metacarpophalangeal.

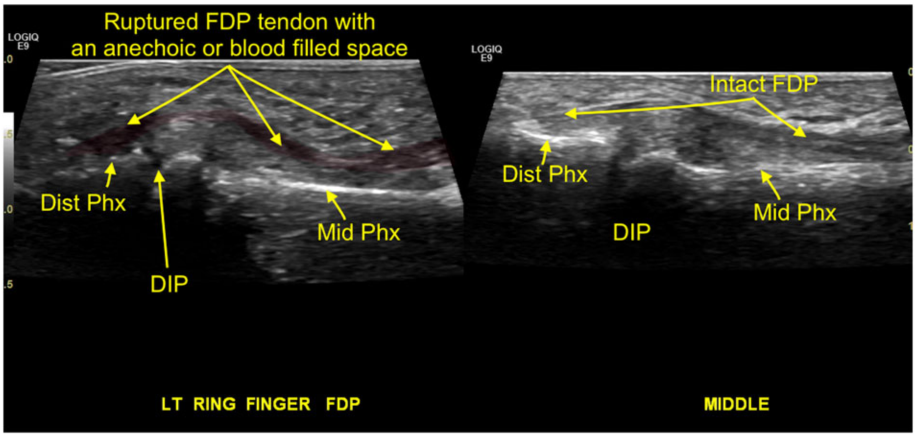

Figure 5 The affected ring finger shows an absence of flexor digitorum profundus (FDP), there is an anechoic space, which once housed the FDP and focal interruption of the fibrillar echo structure of the tendon, compared with adjacent unaffected finger. DIP, distal interphalangeal; FDP, flexor digitorum profundus.

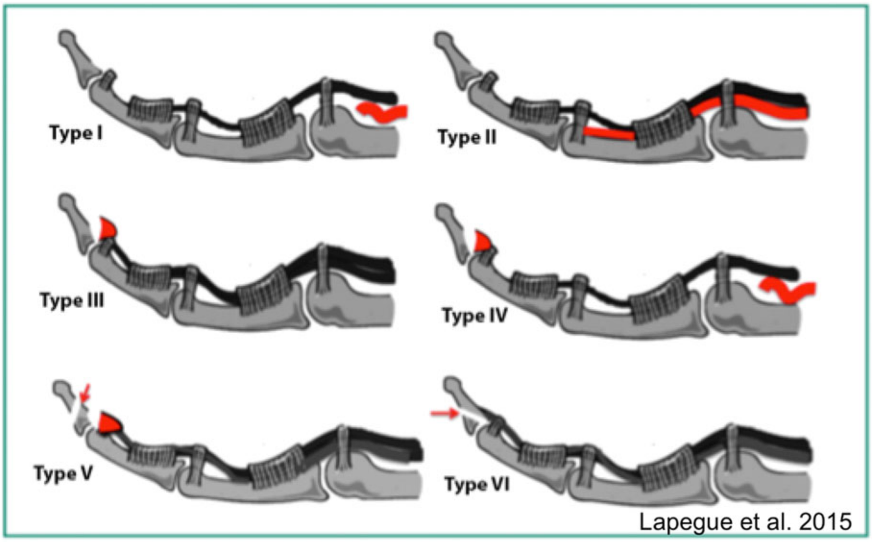

Figure 6 Different types of flexor digitorum profundus (FDP) injuries: Type I the FDP tendon retraction into the palm; and there is significant loss of blood supply to the tendon. Type II results in FDP tendon retraction to the proximal interphalangeal level; and there is a partial blood supply to the tendon. Type III large fracture fragment stuck at the level of pulley A5 with little tendon retraction. Type IV combination of large avulsion fracture of the base of distal phalanx, but the bone fragment is not attached to the FDP tendon, which retracts into the palm. Type V avulsion of the FDP associated with a separate fracture of the distal phalanx. Type VI 'a false mallet finger', describing the insertion of the FDP, remains intact, but the dorsal side of the distal phalanx is fractured. Reproduced with permission from Lapegue F, Andre A, Brun C, Bakouche S, Chiavassa N, Sans N, and Faruch M. Traumatic flexor tendon injuries. *Diagnostic and Interventional Imaging* 2015; **96**: 1279–92. Elsevier Masson SAS. All rights reserved.[9]

exploration.[23] Closed tendon rupture is often overlooked in the acute setting, as there is often minimal clinical deformity leading to a delay in diagnosis.[15] Injuries not recognised at the time of presentation and treated promptly can result in functional impairment of the hand.[1]

When there is suspicion of open or closed tendon injury, based on physical examination, ultrasound should be used to delineate the extent of tendon involvement. The efficacy of ultrasound findings to enable the treating physician to choose between surgical exploration or conservative treatment is well established.[4,24,25]

Annular pulleys

Pathologies affecting the pulleys range from chronic micro-trauma to acute rupture. Micro-traumas are the consequence of chronic repetitive movement of the finger, related to occupational or recreational activities.[4]

Acute rupture is the result of sudden excessive traction on the flexor tendons, such as in elite rock climbers where the finger withstands their entire body weight causing detachment of the A2 pulley and anterior bowstringing of the tendons.[4,9,26,27]

Patients with chronic micro-trauma often present with a clinical 'trigger finger' symptom, a term describing the temporary locking of the affected digit in a flexed position, followed by a snapping sensation over the A1 pulley during extension. The snapping sensation is considered to be due to the increased stiffness and thickening of the A1 pulley.[28] Trigger finger is a common condition, and the most frequent cause is stenosing tenosynovitis.[28,29] The prevalence of the condition has been reported to be close to 3% in the non-diabetic population over 30 years of age and 17% in the diabetic patients.[28,29] The male to female ratio is 6:1, and the most commonly affected digit is the thumb 50%, followed by middle finger 27%, ring finger 14%, index finger 7% and little finger 2%.[28,30] Thickening of the A1 pulley can cause local friction that leads to tenosynovitis and tendon swelling within the narrowed digital canal.[4,31] Some trigger fingers demonstrate abnormalities in the tendon and tendon sheath without thickening in the A1 pulley.[32]

Normal pulleys appear to have three layers, hypoechoic in the central portion and hyperechoic on either side with a thickness that does not exceed 0.3 to 0.5 mm.[9] Abnormal pulleys appear diffusely thickened and hypoechoic (Figure 7), which is a hallmark of trigger finger on ultrasound.[32] Usually, the associated flexor tendons are swollen and appear rounded in short axis compared with the unaffected tendons (Figure 7A). Colour Doppler may demonstrate flow in the setting of an inflamed pulley (Figure 7C).

A study by Guerini *et al*.[33] of 33 fingers, with painful triggering, concluded all affected A1 pulleys appeared thickened and hypoechoic and 91% showed increased vascularity with power Doppler. In the acute phase, evidence of a synovial sheath effusion proximal to the pulley is commonly noted.[4] In chronic cases of repetitive micro-trauma, the pulley appears thickened, heterogeneous and hypoechoic often accompanied by small mucoid

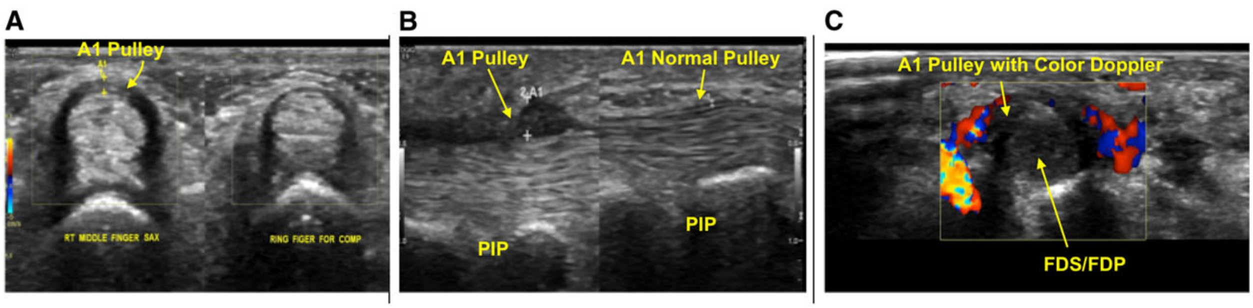

Figure 7 (A) Axial view of A1 pulley, compared with adjacent unaffected finger. (B) Longitudinal view of A1 pulley, compared with adjacent unaffected finger. (C) Colour Doppler demonstrates flow signals within the inflamed pulley. FDP, flexor digitorum profundus; FDS, flexor digitorum superficialis; PIP, proximal interphalangeal.

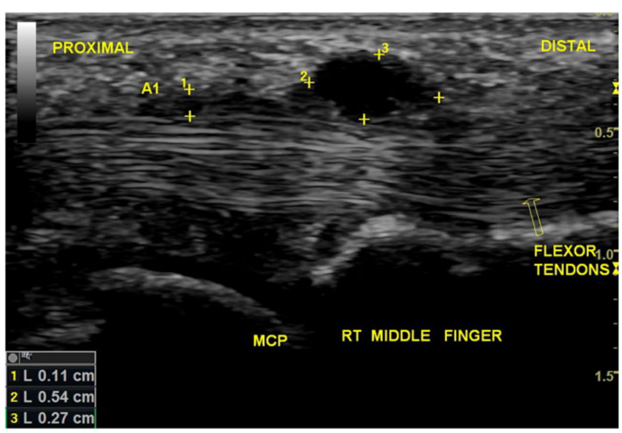

Figure 8 Longitudinal view of A2 pulley with small mucoid degeneration ganglion cysts. MCP, metacarpophalangeal.

degeneration ganglion cysts adjacent to the A1 or proximal edge of the A2 pulley (Figure 8). Comparison with the contralateral side for subtle changes in pulley thickness and tendon swelling can further enhance diagnostic confidence. Trigger finger is essentially a clinical diagnosis with the role of ultrasound being delineation of the cause, level and severity of pathology as well as guiding therapeutic interventions.

Acute detachment of the finger annular pulleys is rare among the general population but commonly seen in elite rock climbers.[4,26] Up to 30% of climbers with finger injuries have pulley ruptures.[10,34] Studies have shown acute pulley ruptures may occur in non-rock climbers, when one loads heavy objects on the fingertips in a similar fashion to the ‘crimp’ grip.[26] The ring and middle fingers are most prone to injury as they are the most commonly used fingers for gripping in free climbers.[4,26] Based on recent biomechanical analysis, excessive traction generated between the pulley and flexor tendon, in eccentric loading, significantly increases the risk of pulley rupture. In rock climber’s fingers, it is the failure of the pulley to withstand the entire body weight, which detaches the pulley resulting in anterior bowstringing of the tendons.[4,26,27] Rupturing of one or more pulleys will result in decreased range of motion and a loss of flexion strength.[27] Misdiagnosis of complete pulley tears may result in secondary osteoarthritis because of flexion contractures of the PIP joint.[4]

Studies of rock climbers have shown acute pulley tears more commonly involve the A2 pulley than the A4 pulley.[4] Clinically, patients report an acute onset of pain on the palmer aspect of the injured finger, accompanied by swelling and an audible snap at the time of injury. This results in a localised haematoma and restricted range of motion, which potentially hinders physical examination.[9,35] Significant bowstringing is not always apparent clinically unless sequential pulleys are ruptured.[5] Differential diagnoses include tenosynovitis, fracture or joint

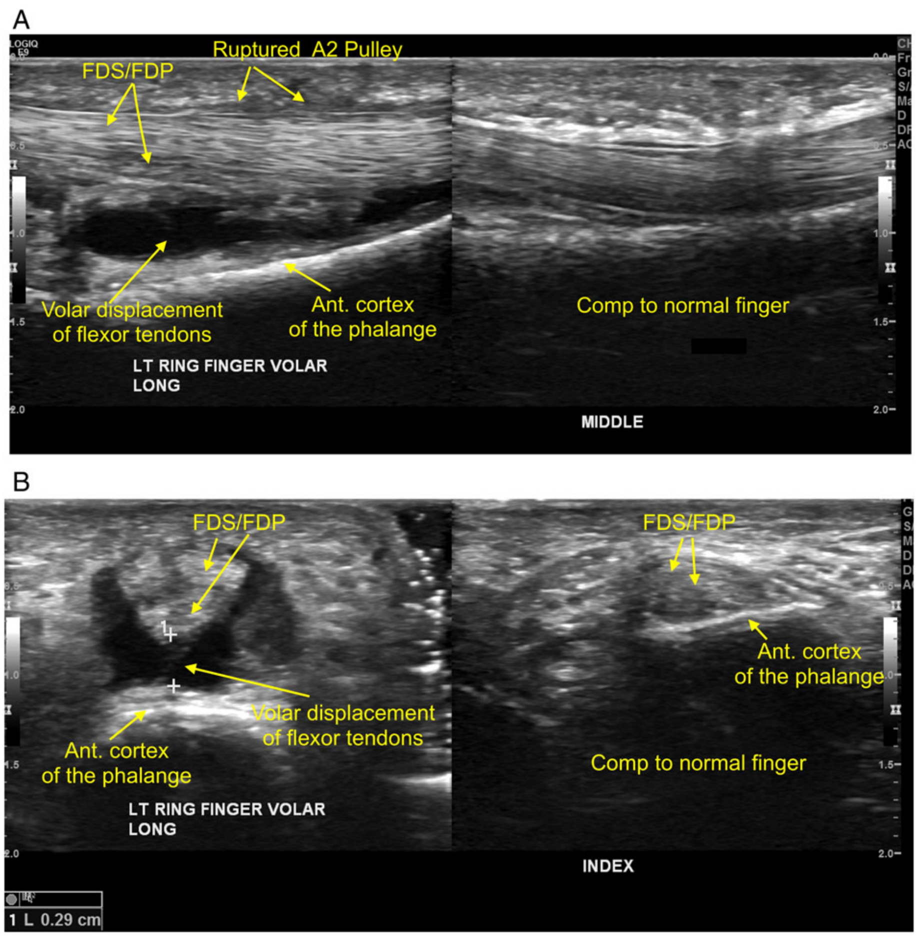

Figure 9 (A) Longitudinal view of A2 pulley rupture, volar displacement of flexor tendon compared with adjacent unaffected finger. (B) Axial view of A2 pulley, there is a large gap between the flexor tendons and the anterior cortex of the phalange compared with adjacent unaffected finger. FDP, flexor digitorum profundus; FDS, flexor digitorum superficialis.

capsule/collateral ligament lesions.[4,35] Distinguishing between pulley strain and partial or complete rupture is rarely possible by clinical examination.[35] In contrast, high-resolution sonography, with appropriate training, can achieve an impressive 98% sensitivity, 100% specificity and 99% accuracy for detecting finger-pulley injuries.[36] Sonographically, the normal distance between the flexor tendons and the anterior cortex of the phalanges is between 0.5 and 1 mm, a gap greater than 1 mm in forced flexion is a sign of injury.[36] A complete rupture of the A2 pulley results in increased volar displacement of the tendons with the bowstringing affect occurring over the proximal phalanx (Figure 9). Partial pulley ruptures show no evidence of bowstringing affect sonographically with the partially torn pulley appearing hypoechoic and thickened. Schoffl VR and Schoffl I divided pulley injuries into four grades to help guide and correlate therapeutic options:[35]

- Grade I pulley strains with no evidence of dehiscence of the tendon from bone.
- Grade II partial rupture of the A2 or A3 pulleys or complete rupture of the A4 pulley.
- Grade III complete rupture of the A2 or A3 pulleys.
- Grade IV complex multiple pulleys ruptured or single rupture of A2 or A3 pulley with associated collateral ligament or lumbrical muscle injury.

Grades I–III injuries involve conservative management. Grade IV injuries usually require surgical repair.[27]

Proximal interphalangeal volar plate injury

The volar plate of the PIP joint is fibrocartilage and can be clearly delineated as an echogenic homogeneous structure underlying the flexor tendons. As a result of forced sudden hyperextension, or crush injuries of the PIP joint,

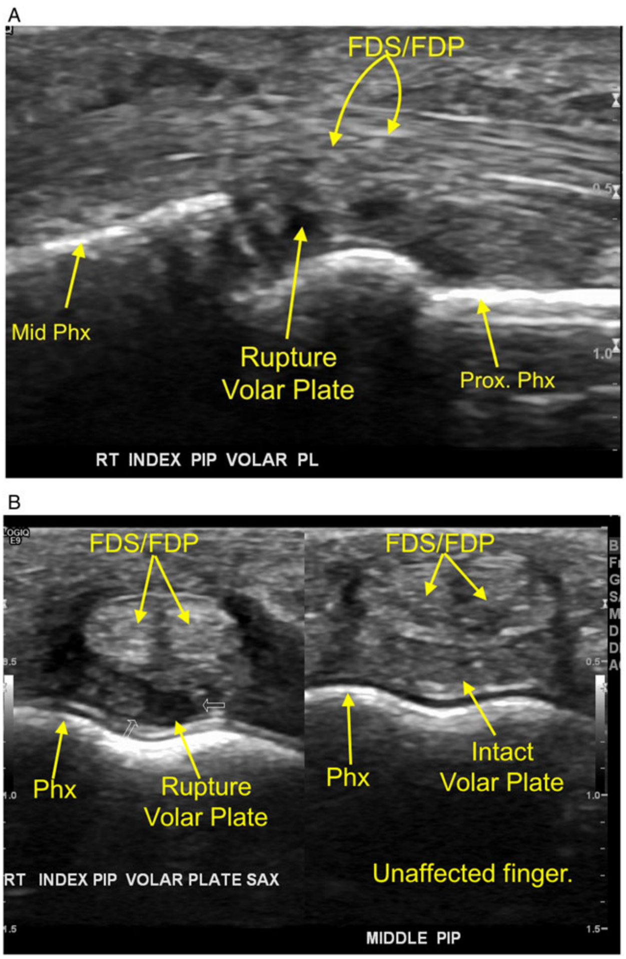

Figure 10 (A) Longitudinal image of the index finger proximal proximal interphalangeal joints shows a complex full thickness tear of the volar plate. (B) Axial view of volar plate at proximal proximal interphalangeal joints shows a full thickness tear compared with adjacent unaffected finger. FDP, flexor digitorum profundus; FDS, flexor digitorum superficialis.

the volar plate may be partial or fully ruptured, usually occurring at the enthesis where it attaches to the base of the phalanx rather than the proximal stronger checkrein ligaments.[37] Volar plate rupture can involve avulsion fractures of the phalangeal base with these injuries often occurring in younger patients who play contact sports.[37] Traditionally, volar plate tears are treated by buddy strapping or immobilisation with a dorsal splint in 30° flexion. Both techniques demonstrate excellent outcomes.[38] Sonographically, a partial tear to the volar plate will present as a hypoechoic cleft while full thickness tears demonstrate a hypoechoic defect separating the volar plate from the phalangeal base (Figure 10). Delayed treatment of an avulsion fragment involving greater than 30% of the articular surface requiring surgical intervention can potentially result in chronic functional loss of the joint and bone deformities.[38] Comprehensive assessment of the volar plate relies on a combination of static and dynamic examination using joint extension as a provocative test.

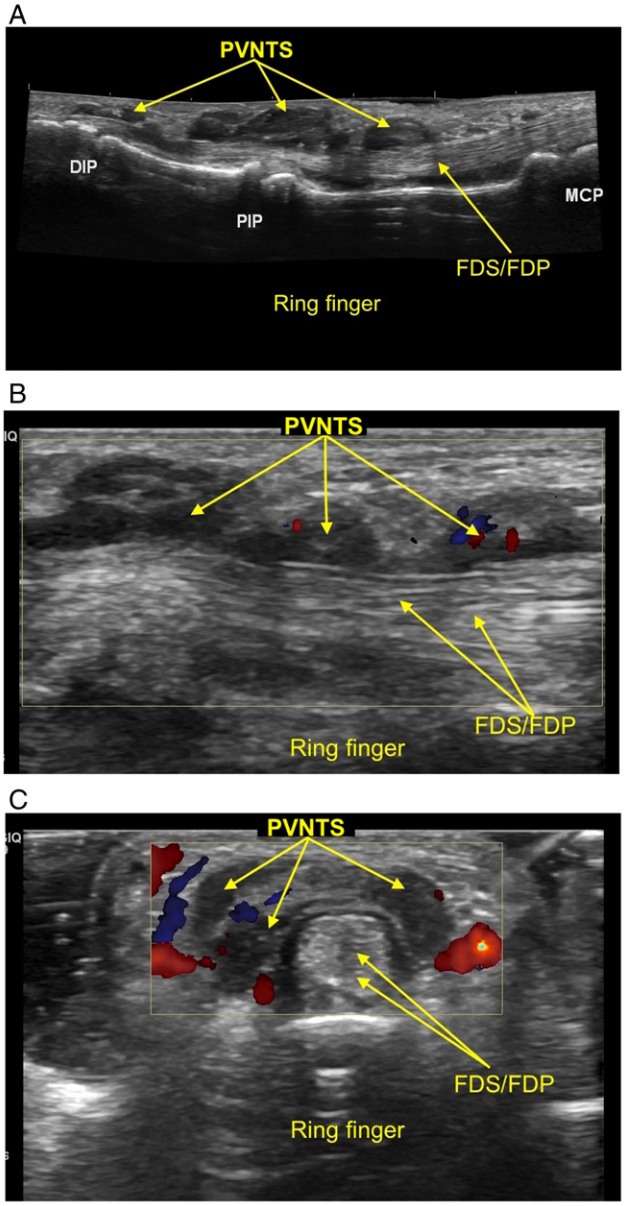

Figure 11 (A) Panoramic ultrasound imaging. Hypoechoic, heterogeneous solid mass with multiple lobulations surrounding the flexor tendon sheath. (B) Colour Doppler imaging demonstrated an increase in internal vascularity of the solid mass. (C) Transverse B-mode and colour Doppler images show the hypoechoic, heterogeneous, solid mass encasing the flexor tendons. DIP, distal interphalangeal; FDP, flexor digitorum profundus; FDS, flexor digitorum superficialis; MCP, metacarpophalangeal; PIP, proximal interphalangeal; PVNTS, pigmented villonodular tenosynovitis.

Flexor tendon sheath tumour – Pigmented villonodular tenosynovitis

Pigmented villonodular tenosynovitis is an extra-articular localised form of pigmented villonodular synovitis (PVNS) frequently referred to as a giant cell tumour of the tendon sheath. They are most common in the middle and index fingers occurring twice as frequently in the volar than the dorsal aspect of the hand. They represent the most common space-occupying lesion of the hand secondary to ganglia.[39]

The characteristic sonographic features of the tumour are typically a homogeneous, hypoechoic mass with sharp margins and a lobulated contour with no posterior acoustic enhancement. They often exhibit internal vascularity on colour Doppler[38] (Figure 11). The lesion has an intimate relationship with the flexor tendon with 6 mm being the average length of tendon contact and the average circumferential tendon involvement being 140°.[40] Dynamic ultrasound is able to demonstrate the relationship between the nodules and the adjacent tendon and tendon sheath. Pigmented villonodular tenosynovitis lesions arise from the tendon sheath and move independently to the tendon during dynamic assessment.[39]

There is no current imaging technique or conclusive clinical presentation that provides a definitive diagnosis of PVNS. PVNS can only be diagnosed with certainty based on histological features including the presence of intracellular and pigments of subsynovial haemosiderin, the presence of macrophage multinucleate giant cells, foamy histiocytes and inflammatory cells.[41]

Conclusion

Pathology affecting the FDA can be due to acute injuries or chronic micro-trauma with each pathology pattern having unique ultrasound characteristics and treatment management. Early diagnosis and timely treatment are required to avoid functional impairment of the hand. In skilled hands, ultrasound can depict a broad spectrum of abnormalities enabling the treating physician to choose between surgical exploration and conservative treatment.

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