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A Comprehensive Synthesis of the Current Knowledge regarding the Anatomy and Histology of the Triangular Fibrocartilage Complex of the Wrist Joint

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ABSTRACT

Ever since its description, the triangular fibrocartilage complex (TFCC) of the wrist joint remain as an enigmatic topic. The main reason for the controversies around is the lack of concrete evidence regarding its attachments, morphology, biomechanical aspects, and radiological appearance. Similarly, the role of TFCC in chronic non-traumatic wrist pain is also remains as a point of debate. The orientation of TFCC and associated ligaments stands as the reason for varied documentation concerning imaging techniques. With the growing body of evidence, it is imperative to amalgamate the findings regarding the complex and its microscopic anatomy. The knowledge can be used for concomitant wrist surgeries and potential arthroscopic procedures. The present review tries to systematically review the anatomy, descriptions, and histology of TFCC. At the end of the review, we would like to find the answer to the question: Is TFCC a distinct ligamentous structure? What is the neurovascular pattern related to it?

Introduction

The wrist joint is a complex one as it achieves multiple directional motions, flexion-extension, radial and ulnar deviation, and pronation-supination. The wrist joint is mainly composed of the midcarpal, radiocarpal, and distal radioulnar joints.[1] The distal radioulnar joint is one of the key joints in the upper limb which offers stability and performs key functions pertinent to upper limb. Stability of this joint is dependent on the congruity of "the radius and ulna, the pronator quadratus, the extensor carpi ulnaris, the triangular fibrocartilage complex (TFCC), and the interosseus membrane of the forearm." [2] The complex anatomy of the ulnar side of the wrist offers great challenges in understanding, diagnosing, and treating its pathologies. The complex nature of this structure makes it difficult to arrive at a consensus in the management of pathologies in this joint. During the past few decades, a sea of information about the ulnar side of the wrist was made available due to continued efforts to understand it. Ulnar wrist pain is one of the most common wrist problems perceived by hand surgeons. It may be either acute or chronic and include the following causes fractures, dislocations, ligament injuries, avascular necrosis, and degenerative changes affecting the ulnar carpus and distal radioulnar joint. In the elderly groups, wrist pain has been emerging as an important treatment modality making the entire focus to be on the wrist joint. It has been noted that TFCC (triangular fibrocartilage complex) remains the most recognized cause of ulnar wrist pain. [3] This urges us to analyze the complex anatomical and biomechanical structure of TFCC. The triangular fibrocartilage complex (TFCC) is a ligamentous fibrocartilaginous structure located in the ulnar aspect of the human wrist separating the radiocarpal and distal radioulnar joints. TFCC has seven distinct components: the articular disc (AD), the volar radioulnar ligament (VRUL), dorsal radioulnar ligament (DRUL), the ulnolunate (UL), the ulnotriquetral ligaments (UTq), the subsheath of the extensor carpi ulnaris (SS-ECU) tendon and the ulnocarpal meniscoid structure (UCM). (Fig 1) Mechanical and dynamic stability of the wrist joint relies on fine interactions among these components of TFCC. In the dynamic condition, a tripod of stabilizers acts together to ensure stable functioning of the distal radioulnar joint (DRUJ). Structures constituting the tripod are bony contact between adjacent bones, TFCC complex which tends to act as an intrinsic stabilizer, and distal forearm structures acting as distal stabilizers. Thus, treatment for disorders involving DRUJ mandates a deeper understanding of the stabilizers, especially the TFCC. The cardinal function of TFCC is to cushion and support the small carpal bones in the ulnar aspect of the wrist. In addition, TFCC keeps the forearm bones (radius and ulna) stable and together when the hand grasps or the forearm rotates. An injury or tear to the TFCC can manifest as chronic wrist pain in patients leading to persistent morbidity. Depending on the type of injuries, two types of TFCC tears can manifest: a) Type I tears are called traumatic tears.[3, 4] Falling on an outstretched hand and excessive arm rotation are the most common causes that could lead to this pattern of tears. b) Type 2 TFCC tears are degenerative or chronic. They occur due

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to wear and tear of the cartilage associated with increasing age. Some inflammatory disorders such as rheumatoid arthritis or gout may also contribute to Type 2 TFCC tears.[4] The wrist joint is densely innervated by neurons especially mechanoreceptors to perform high-quality proprioceptive functions. So, pathologies involving the wrist joint result in significant pain owing to the intense neuronal innervation in the form of free nerve endings. Ulnar-s ided wrist pain is one of the most common clinical disorders affecting the wrist and is due to injuries or degenerative diseases. The mechanism of chronic wrist pain and the sensation of wrist instability can be studied by observing the distribution pattern of mechanoreceptors in TFCC. The free nerve endings conducting pain sensation are predominantly distributed in the ulnar and dorsal areas.[5] Similarly, studying the pattern of vascular distribution can facilitate surgical planning and also provide insight into the pattern of suturing thereby preventing degeneration.[6] Extra-articular tissues especially nerves and tendons are at risk during wrist arthroscopy. Complications during arthroscopic procedures develop due to a multitude of reasons including excessive traction, positioning of the arm, establishing the portals, and procedure-specific injuries. Poor positioning of portals may risk the integrity of articular cartilage, ligaments, tendons, cutaneous nerves, and vascular structures. [7] In the arthroscopic thermal shrinkage procedure, non-ablative thermal energy is discretely and carefully applied, and the physical heat denaturation of collagen shrinks the ligaments of TFCC.[8] At 65 °C collagen undergoes structural changes as the triple helix unwinds and denaturation begins. As the contracted collagen mass loses its microscopic fiber organization, its physical properties change and the tissue becomes increasingly stiff. [9] Besides, electrothermal treatment eliminates neuronal tissue and may function to relieve pain through a denervation effect. [10] All of the above-mentioned pathological abnormalities and surgical procedures warrant comprehensive knowledge of the anatomical relationships and histo-morphology of TFCC. Knowledge regarding the anatomical relations, histology, and neurovascular pattern of TFCC shall be highly yielding for arthroscopic surgeons while planning for surgeries involving wrist joints.[6] Consequently, diminished rates of structural injury and better reconstruction of wrist joints are expected to be achieved.11 It is also useful for radiologists to interpret scans of patients presenting with chronic wrist pain.

History of the triangular fibrocartilage complex of the wrist joint

The most complicated and crucial joint in the upper extremity is the distal radioulnar joint. The stability of the joint is contributed by the extensor carpi ulnaris, pronator quadratus, interosseous membrane of the forearm, congruity of radius and ulna, and TFCC, being one among them, are responsible for the stability. Ulnar-sided wrist pain has been common nowadays, and treatment and ability to comprehend this region remains difficult. There has been an increasing review regarding this area, but the literature and management remain scarce. For better treatment plans, postoperative care, intervention, modulation of outcome of disease, and rehabilitation programs, understanding the anatomy is essential. Further knowledge regarding the anatomy is correlated with biomechanism of pain, pathology, and operative procedures. Morphological design of the present-day wrist joint and forearm bones can be mapped back 400 million years.[5] There is a marked change in the transition of wrist function to a weight-bearing structure. The morphology and biomechanical construct of wrist and forearm bones shifted according to the demands from transmission of weight to arm swinging to locomotion on legs. The ability for various rotations of the forearm, usage of tools, for carrying things defending ourselves in the environment depends upon the stability and development of DRUJ and forearm and they are the necessary considerations for humans to evolve various capabilities. The three important contributions for DRUJ to develop evolutionarily involve the following 1) Ulna being recessed distally from the carpus, 2) The growth of Triangular fibrocartilage 3) the formation of stable DRUJ. Before the development of the above structures there existed restricted rotation due to articulation of the pisiform and triquetrum with the styloid process of the ulna and also between the distal aspects of the ulna and radius there was the occurrence of syndesmosis. The major role in the transmission of weight from carpus was mainly due to the structural evolvement of the ulnocarpal meniscoid.

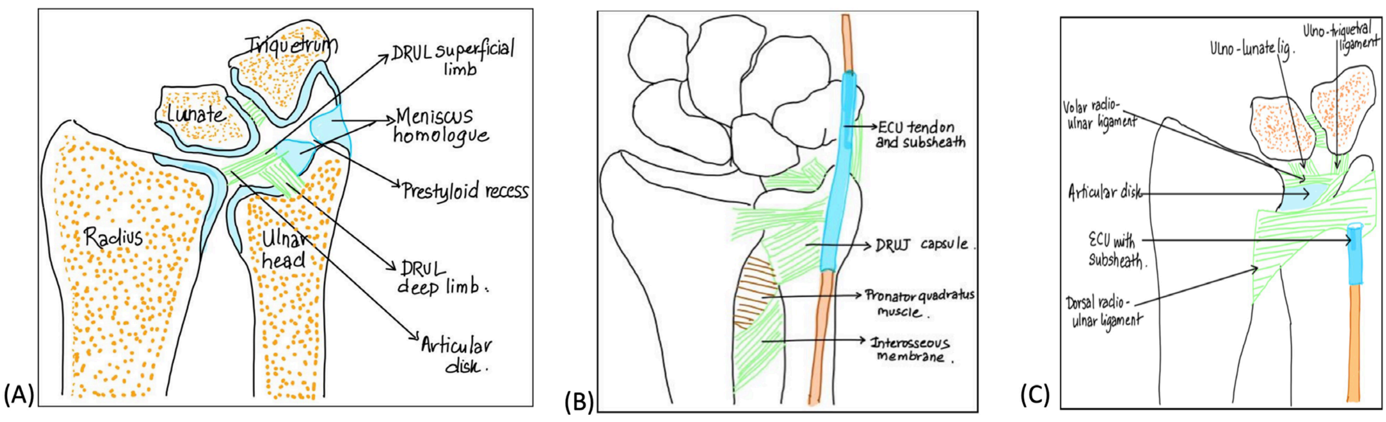

Fig 1: (A) TFCC Anatomy in Coronal Section ; (B) Schematic diagram of TFCC from dorsal aspect ;(C) Schematic diagram to show the internal view of TFCC

Components of the Triangular Fibrocartilage Complex

TFCC can be viewed three-dimensionally as a proximal ligamentous component, distal hammock-like structure, and the ulnar collateral ligament.4 It has both avascular and vascular portions. The peripheral ligamentous part remains vascularized and the horizontal cartilaginous part is avascular. The biomechanical functions of TFCC can be viewed as follows: it acts as a stabilizer for the distal radioulnar joint and the ulnar carpus, helps in the transmission of the axial load, and serves as a cushion for the ulnar carpus.[5]

Articular disc

It is a triangular-shaped structure as described by in the axial plane.[6] TFCC has been subdivided into the proximal, distal, and the ulnar component. The distal component forms the floor by a hammock-like structure that covers the articular disc.[6] It forms a part of the radioulnar ligament rather than forming an individual component of TFCC. It has central compression forces which leads to reduced blood supply and cartilaginous metaplasia.[7]

Mikic et al., studied 180 wrist joints to study the variations of the articular disc among different age groups.[8] The articular disc appeared as a smooth white structure with a glistening surface in specimens of age <30 years. In the late thirties, the disc appeared yellowish, matted with irregular surface forming pitting and fibrillation, and became shredded with less elasticity. Erosions, perforations, ulceration, and thinning were noted in some cases. All discs were present with some abnormalities among the 50 years age group.

Nakamura et al in their study stated that the disc appeared thinner at the radial part and thicker at the ulnar part.[9] Macroscopically Benjamin M et al., and Totterman T et al., could not appreciate the disc from the radial articular surface.[10, 11] A clear-cut microscopic visualization between radial articular cartilage and the radial part of the disc was given by Nakamura T et al..[12] The ulnar notch of the radius has been referred to as the sigmoid notch or incisura ulnaris radii and is also referred to as the radial attachment. This portion represents the central transition of the disc from the fibrocartilaginous disc into hyaline cartilage. No direct bony attachments were seen in any of these studies.[10, 12, 13]

Benjamin et al. and Zhan, Li, et al. observed separate attachment sites for the ulnar side of the disc and it is divided into two bands of collagen fibres.[10, 13] The proximal fibers attached at the fovea and the distal fibres to the ulnar styloid process form the ulnar attachment. It's an area of depression situated dorsally between the ulnar styloid process and the ulnar head. These fibres of the ulnar attachment have been termed as proximal and distal lamina separately. The proximal lamina had vertically oriented fibers, and the distal lamina had horizontally oriented fibers.[13]

Two distinct fiber bundles were described by Benjamin et al. and termed as upper and lower lamina.[10] The fibers of the upper lamina originate from the ulnar head and courses through the radial side of the styloid process and terminates in bony attachments. Blending of fibers from the disc and the radioulnar ligament has been noted by the authors at the ulnar attachment. The fibers of the lower lamina fuses with extensor carpi ulnaris sub-sheath and the ulnar collateral ligament.[10]

Radioulnar ligament surrounds the articular disc at its proximal part and its central fibers fuses with the proximal side of the disc. The meniscus homologue has been attached to the distal part of the disc as stated.[9] Some additional bands of collagen fibers has been noted to extend from the disc to the tip and base of the styloid process as observed by Totterman and Miller et al.[11] Studies showing the relation between disc perforations and age have been conducted by Mikic as well as Viegas and Ballantyne. [8, 14] Most of the studies conducted showed that ulnar attachment is not a part of the disc itself instead it is part of the radioulnar ligament.

In the study conducted by Mikic between the age group of 20 and 30 years, all of the discs with perforation showed degeneration, while only one of the wrists showed no degenerative signs.[8] Other wrists with perforation showed advanced degeneration showing irregular, thin, and shredded edges. Twenty-three out of 45 wrists used in the study showed oval, round, or irregular perforation at the center.18 wrists showed perforations as fissures along the radial rim. The study was conducted in a 23 years age group, it didn't show any signs of degeneration. Among the three, the central part of the disc showed long sagittal fissures. The entire disc was fully perforated among one of the wrists.

Histology of the articular disc

The articular disc was found to comprise fibrocartilage as proposed by 4 studies.[6, 12, 15, 16] It was shown in one study that they consist of densely packed collagen bundles which at the ulnar limit became parallelly oriented fibers. Semisch et al.16 It was proposed that at the periphery of the disc has only fibroblasts and the central disc was composed of fibrocartilage surrounded by blended fibers of collagen and elastic fibers.[15]

The proximal part of the disc has radio-ulnar oriented fibers while the distal part has abundance of chondrocytes in the collagen matrix was detected in a study by Nakamura and Yabe. [9] There were two separate superficial layers in an arch like pattern and one deep layer impregnated within the disc. Short banded wave like randomly arranged fibers in sheets are observed in the central part of the disc with an angle of up to 90 degree in three dimensional view. This variation was reported by Chidgey et al.[17] Also variations in pattern were noted between immature wrists and adults. Wavy pattern and the distinction between two layers were prominent in immature wrists at the radiocarpal surface. In younger adults, only early fibrillation was noted in the superficial layer.[17] The collagen fibers were found in abundance at 1-2 mm of the disc in its radial aspect. The fibers were randomly oriented at the disc than the distal radius, which had longitudinally oriented fibers, and the radial attachment of the disc had thicker collagen bundles than the other part of the disc. [17]

Less number of elastic fibers were observed by several authors in the disc.[15, 17] In late twenties it was noted that chondrocytes gradually replaced fibroblasts thereby decreasing the number of elastic fibers which ultimately became like fragments and less cellular (Fig. 2). Mucoid degeneration with calcification or chondrocyte proliferation changes with fibrillation mostly occurred at the proximal surface of the disc while its distal part remained normal. Thinner central areas of the disc was mostly affected than

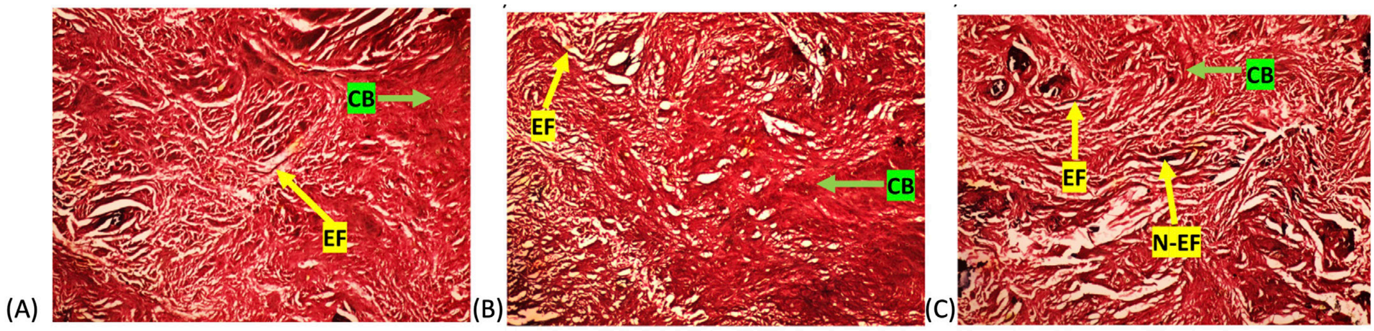

Fig. 2: Transverse section of the proximal part of the articular disc. CB: Collagen bundles, EF: Elastic fibers, N-EF: Nuclei of elastic fibers (Verhoef van Gieson stain, A: 4X, B: 10X, C: 40X)

the thicker peripheral parts.8 Macroscopic calcifications with disc perforations have been observed by the following authors Mikic et al and Viegas and Ballantyne et al who noted calcium pyrophosphate dihydrate crystals in old cadaveric wrists. [8, 14]

Vascularization and Innervation of the articular disc

Avascularity was noticed in the central 80% and radial attachment by several authors.[15, 16, 18] The radial articular cartilage prevents vascular development from the radial side.[18] Sparse vascularization was seen in peripheral 15–25%, especially in the dorsal, volar, and ulnar parts of the disc in fewer studies.[15-17] The articular disc was demonstrated to have blood supply compared to other areas of the components of TFCC.[19]

Nervous tissue was not found in the central part of the disc.[20] In the ulnar part of the disc free nerve endings were observed.[15, 19] Nerve endings were specifically located at the peripheral portion in the ulnar side of the wrist. [15]

Radioulnar Ligaments (RUL)

The radioulnar ligament consisted of two fibrous bands surrounding the central cartilaginous disc. These fibrous bands were named volar and dorsal and were found to measure 2 mm in thickness.[7] Different forms of the central portion of this ligament have been described by various studies.[4, 6] This ligament was acknowledged to connect the radius with the ulna and it is located at the dorsal and volar side of the disc.[2, 11-13, 15-17] Visually articular disc and radioulnar ligament cannot be distinguished through gross anatomy.[17] In another study, the difference was discernible between the above structures.[11] One study showed that wrist capsules and radioulnar ligaments were intermixed with each other peripherally.[21]

The dorsal and volar edges of the sigmoid notch form the site for the radial attachment of the disc and it is wider in appearance according to the following studies.[4,6,13,17] It is shown that the cartilaginous attachment is directed towards the radius whereas the radial attachment was found to impinge on the distal radius directly.[10,12,13] Shigemitsu et al. on the contrary described the ligament with no attachment to the radius instead being attached to the proximal portion of the articular disc.[20]

The ulnar attachment has two separate attachments Chidgey et al. and Ekenstam and Hagert.[7, 17] It was observed that separate attachments and the ulnar attachment form a distinct ligament similar to the radioulnar ligament. Another attachment of fibers was observed with dorsal and volar radioulnar ligaments attached to the base and the styloid process.[7] It was demonstrated by Chidgey et al. that the ulnar side of the head forms the attachment site for proximal collagen bundles and the styloid process partly blends with the sub sheath of the extensor carpi ulnaris tendon.[17]

It was noted by the following authors a distinct superficial and deep portion of the radioulnar ligament.[2, 22, 23] Ishii et al. noted that the superficial and deep parts extend towards the ulnar attachment and this split from the dorsal and volar radioulnar ligament was located midway between the radial and ulnar attachments.[2] It is shown that the superficial ligament is traced towards the distal ulnar capsule and the deep ligament is drawn towards the ulnar styloid base. [2] Hence, it was concluded that the deep ligament showed foveal attachment while the majority of the ulnar part of the disc without an ulnar styloid was enclosed by the superficial ligament.[2] Another study showed that the superficial portion was attached at the radial side of the styloid process while the deep limb was attached to the fovea.[22] It was showed that the superficial part showed attachment to the tip of the styloid process covering up to distal 13% while the deep part had foveal attachment extending up to the proximal 81% of the styloid process.[23]

There was a wider degree of variations noted by the authors in the attachment areas. The attachment at the foveal area was narrower than the ulnar styloid process attachment.[12, 22, 23] It was noted that the footprints of the superficial part were three times smaller compared to the deeper part. Asymmetry was noted with the footprint of the deeper portion, especially at the dorsal side and an accessory footprint was seen in 47% of this dorsal portion.[23]

A different view regarding the superficial part of the radioulnar ligament was offered by Horiuchi et al.[24] The superficial part of the superficial radioulnar ligament was similar in architecture to the cruciate ligaments of the knee. Difference was observed in dorsal and volar orientation between the superficial and deep part of the ligament. The radioulnar ligament was attached to the volar side of the articular disc and the dorsal part of the styloid process. The deepest part of the ligament is attached at the level of the middle third of the styloid process. On the contrary, the superficial part of the radioulnar ligament attaches at the level of the distal third of the styloid process. This difference was noted between the level of the two attachments.[24] It was shown that fibers situated near the ulnar protrusion of the volar ulnar rim of the radius were attached to the sigmoid notch and connected with the dorsal side of the ulnar styloid process.

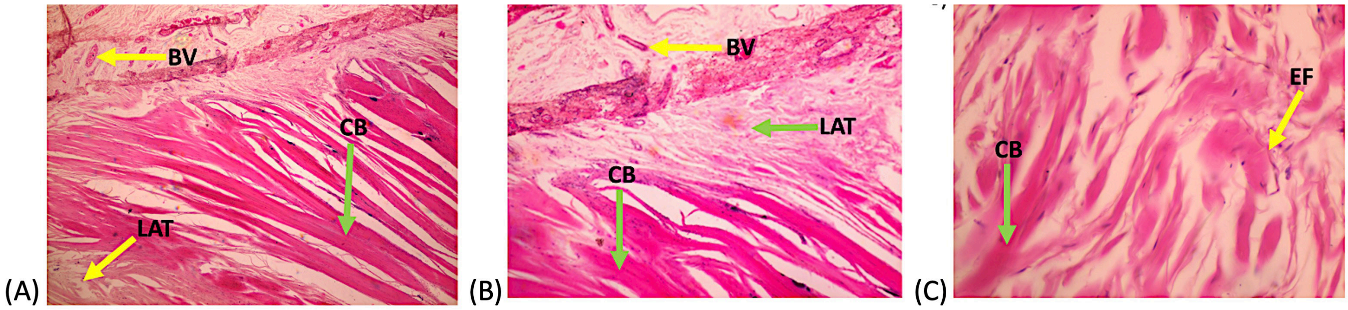

Fig. 3: Transverse section of the distal part of epiligament (dorsal radioulnar ligament). CB: Collagen bundles, LAT: Loose areolar tissue, BV: Blood vessel, EF: Elastic fibers, (H&E stain, A: 4X, B: 10X, C: 40X)

Table 1: Brief summary of the previous studies documenting the morphometric and histological findings of the articular disc

Study	Morphology	Histology	Elastic fibres	Vascularity	Neural density
Benjamin et al [10]	Fibrocartilage extending from ulnar notch to the carpal surface of radius	Densely packed interlacing	Fewer	Avascular	Not applicable
Chidgey et al[17]	Split lines orientation differs on the surface of the disc on both the attachment sites of radius and ulna	Wavy pattern of fibres in central part of disc and at the radial attachment thicker and abundance of collagen bundles were seen	Less number of elastic fibres	Central portion avascular and the peripheral part of the disc showed some vascularity	Not applicable
Bednar et al[18]	Fibrocartilage which blends with articular cartilage of radius	Densely packed collagen fibres	Not applicable	Inner portion of the disc showed avascularity	Not applicable
Nakamura et a[16]	Triangular shaped forms a hammock like structure	Fibrocartilage	Fewer	Not applicable	Not applicable
Ohmuri and Azuma et al[15]	Fibrocartilage made up of cells and matrix originate from the ulnar side	Central disc had fibrocartilage with peripheral fibroblasts	Less number	Peripheral part alone had vascular supply	Only the peripheral part of the disc had few nerve fibers
S. Rein et al [19]	Fibrocartilaginous structure and main stabiliser of the distal radioulnar joint	Densely packed interlaced	None	Radial and central areas were avascular	Less neural density
Semisch et al [16]	Made up of fibrocartilage	Densely packed interlaced and parallel collagen bundles	None	Central part showed avascularity	Not applicable
Nakamura and Yabe et al[9]	Disc appeared thinner at the radial part and thicker at ulnar part	Proximal part had radioulnar oriented fibres while distal part had abundance chondrocytes in dense collagen matrix.	Fewer	Central avascularity was seen	Not applicable
Nandini et al 2023 (Unpublished data)	Triangular structure extending from ulnar notch to radius	Densely packed interlacing	Fewer	Peripheral part showed sparse vascularity	Less neural density seen

Table 2: Brief summary of the previous studies documenting the morphometric and histological findings of the radioulnar ligaments

Study	Morphology	Histology	Elastic fibres	Vascularity	Neural density
Benjamin et al[10]	Dorsal radioulnar ligament blends with tendon sheath and extends from radius to ulna. Volar radioulnar ligament extends from radius to the disc.	Loosely packed fibres	Fewer	Higher vascularity compared to the disc	Not applicable
Chidgey et al[17]	Origin from the dorsal and palmar aspects of the sigmoid notch of the radius and insert into ulna	Collagen bundles arranged in parallel fashion.	More in number compared to disc	Well vascularised	Not applicable
Bednar et al[18]	These ligaments connect the radius with ulna and enclose the disc	Collagen fibres arranged in bundles	Not applicable	Increased vascularity compared to the disc area	Not applicable
Nakamura et al[6]	Attached to the radius and ulna	Densely packed collagen fibres	More in density compared to the disc	Not applicable	Not applicable
Ohmuri and Azuma et al[15]	Ligaments extend from radius to ulna	Collagen bundles noted	More in number	Well vascularised	Densely innervated
S. Rein et al[19]	Attached with radius and ulna and principal stabiliser of the distal radioulnar joint	Densely packed collagen bundles	Fewer in number	Increased vascularity	Higher neural density
Semisch et al[16]	They have their ulnar insertion at the fovea and the base of the ulnar styloid	Densely packed parallel collagen fibres with longitudinal wave like pattern	Elastic fibres were classified as none	Highly vascular	Not applicable
Nakamura & Yabe et al[9]	Attached from fovea to the base of styloid process	Dense collagen fibres	Fewer	Increased vascularity noted	Not applicable
Nandini et al 2023 (Unpublished data)	Ligaments connect the radius from ulna and enclose the disc	Densely packed interlaced or parallel collagen fibers	Classified under None	Rich vascularity	Increased neural density

This attachment was referred to as the volar ulnar capsule and could not be differentiated from the radioulnar and short radiolunate ligament.[25]

The Radioulnar ligament was not considered to be a ligamentous component of the articular disc as it didn't connect the radius and ulna, rather considered as distal hammock structure. They put forth that the triangular ligament surrounds the true radioulnar ligament thereby forming the proximal ligamentous part of TFCC.[4, 6] This ligament extends from the fovea to the sigmoid notch at the dorsal and volar portion. Fibro-cartilaginous component seen in the radial part intermingled with the articular surface of the articular disc.

Histology of the radioulnar ligaments

A significant difference was shown by polarized light microscopy between the articular disc and the radioulnar ligament. This difference could not be appreciated between them by hematoxylin and eosin-stained sections (Fig. 3). The radioulnar ligament showed distinct longitudinal collagen bundles with larger gaps between the waves and the pattern was less severe.[17] A mean ratio of 1.27 was found between collagen 1 and 3 fibers of this ligament. This ratio was lower in the deeper part when compared with the superficial part demonstrating the difference in mechanical properties.[22] Dorsal and volar radioulnar ligaments have a similar

Table 3: Brief summary of the previous studies documenting the morphometric and histological findings of the Ulno-triqueteral ligament

Study	Morphology	Histology	Elastic fibres	Vascularity	Neural density
Benjamin et al[10]	Ligament connecting the distal ulna to the triquetral bone	Less densely packed collagen bundles with loose connective tissue	Fewer fibres	Shows vascularity	Not applicable
Chidgey et al[17]	Attached from the ulna to the triqueterum	Parallel longitudinally oriented collagen fibers	Less in number	Exhibits some vascularity	Not applicable
Bednar et al[18]	Ligament extends from ulna to triquetrum	Less densely packed collagen bundles	Not applicable	Shows vascularity	Not applicable
Nakamura et al[6]	Extend its attachment to ulna & triquetrum	Collagen fibres arranged in less densely packed bundles	Fewer	Not applicable	Not applicable
Ohmuri and Azuma et al[15]	Proximally to volar radioulnar ligament and distally to volar part of triquetral bone in fan shaped form in oblique direction	Matrix consisted of collagen fibres and cells with loose connective tissue	Fewer elastic fibres	Increased vascularity	Higher neural density
S. Rein et al[19]	Shows attachment to ulna and triquetral bone	Less densely packed collagen fibres	Lesser elastic fibres	Shows vascularity	Shows neural density
Semisch et al[16]	Volar ligament connecting the distal ulna to triquetral bone	Parallel oriented less densely packed collagen fibres	Fewer	Increased vascularity	Not applicable
Nakamura & Yabe et al[9]	Attachment from ulna to triquetral bone	Less denser collagen bundles with loose connective tissue	Elastic fibres were less in number	Shows vascularity	Not applicable
Nandini et al 2023 (Unpublished data)	Proximally attached to volar radioulnar ligament and distally to triquetral bone in fan shaped manner	Mixed tight and loosely arranged collagen fibres with loose connective tissue	Elastic fibres were classified from none to very less	Higher vascularity was seen than the ulno lunate ligament	Higher distribution of nerve fibres seen

morphology in general. However, slight variations were noted between subjects with parallel or interlaced fiber bundles. These fibers were packed either densely or had a mixture of dense and loose parallel fibers oriented in a radioulnar direction.16 Compared to the margins surrounding the disc, the fiber bundles enclosing the fascicles have thicker and more abundant vascularization.[16]

Vascularization and Innervation of the radioulnar ligaments

A good amount of vascular supply was noted to the dorsal and volar radioulnar ligament with the volar radioulnar ligament having a higher number of blood vessels.[17, 19] The dorsal and volar margins of the radioulnar ligament with loose epifascicular connective tissue had thicker and better vascularization in comparison to the margins of the disc. Insertion parts of the ligament sometimes showed tight

Table 4: Brief summary of the previous studies documenting the morphometric and histological findings of the ulno-lunate ligament

Study	Morphology	Histology	Elastic fibres	Vascularity	Neural density
Nakamura et a[16]	Proximally attached to volar ligament and interposed with disc and distally attached to lunate bone	Collagen fibres in densely packed bundles seen	Very less elastic fibers	Not applicable	Not applicable
Ohmuri and Azuma et al[15]	Fan shaped ligamentous structure extending from ulna to lunate bone	Densely packed collagen fibres with loose connective tissue	Lesser number of elastic fibers	Reduced vascularity	Less distribution of nerve fibers
S. Rein et al[19]	Proximally from distal ulna to lunate bone	Parallely oriented densely packed collagen bundles	Classified under none	Decreased blood supply	Reduced innervation seen
Semisch et al[16]	Attachment seen from distal ulna to lunate bone	Densely packed collagen bundles	Elastic fibers were classified as none	Decrease in number of blood vessels	Not applicable
Nakamura & Yabe et al[9]	Fan shaped structure extending from unla to lunate bone	Parallel arranged thicker collagen bundles	Fewer elastic fibers	Reduced vascularity seen	Not applicable
Nandini et al 2023 (Unpublished data)	Ligament attached from distal ulna to lunate bone in fan shaped manner	Mixed tight and loose parallel arranged collagen fibres	Less elastic fibres	Decreased vascular supply	Decreased innervation was seen
Benjamin et al[10]	Extending from distal part of articular disc close relation to distal radioulnar ligament having meniscus appearance	Mixed tight and loose parallel collagen fibres	Increase in elastic fibres	Increased blood flow	Not applicable
Chidgey et al[17]	Attachment at the triqueterum, ulnar wrist joint capsule, fifth metacarpal base and the hamate bone	Mixture of loose and tight collagen fibres	More number of elastic fibres	Increased vascularity	Not applicable
Bednar et al[18]	From ulnar capsule to fifth metacarpal base	Parallel arranged collagen fibers with loose connective tissue	Not applicable	Well and richly vascularised	Not applicable

interstitial septa with blood vessels, which were absent in the middle parts of the ligament.[16]

Radioulnar ligaments had free nerve endings especially the sensory nerves with a mean density of 3.1 per mm2 (SE ± 1.1).[15, 19, 20] Shigemitsu et al., noted that the total mean density of neural elements was found similar to the meniscus homolog with a total density of 6.0 per mm[2.20] The mean density of single nerve fiber was 1.6 per m[m2] for perivascular neural nets had 0.1 per mm2 and the nerve fascicles had 1.1 per mm^2 density. Ruffini, Vater-Pacini, Golgi-Mazoni, and unclassifiable corpuscles were seen in the form of sensory corpuscles.[20]

Meniscus homologue

This structure is situated between the ulnar part of the wrist capsule and the ulnar border of the superficial part of the radioulnar ligament.[2] The meniscus homologue is defined as meniscus when viewed coronally.[9] It was described as smooth, synovial fold which functions as the ulnar internal

Table 5: Brief summary of the previous studies documenting the morphometric and histological findings of the ulno-carpal meniscoid

Study	Morphology	Histology	Elastic fibres	Vascularity	Neural density
Nakamura et al[6]	Attachment at the triqueterum, ulnar wrist joint capsule, fifth metacarpal base and the hamate bone	Parallel arranged collagen fibers with loose connective tissue	Increased number of elastic fibers	Not applicable	Not applicable
Ohmuri and Azuma et al[15]	From ulnar capsule to fifth metacarpal base	Mixture of loose and tight collagen fibres	More fibers	Well vascularised	Highly innervated
S. Rein et al[19]	Attachment at the triqueterum, ulnar wrist joint capsule, fifth metacarpal base and the hamate bone	Mixed tight and loosely packed parallel arranged collagen fibers	Few to more number of fibers	Good amount of blood supply	Increased distribution of nerve fibers
Semisch et al[16]	From ulnar capsule to fifth metacarpal base	Mixed tight and loosely packed parallel arranged collagen fibers	Increase in distribution of nerve fibers	Increase in number of blood vessels	Not applicable
Nakamura & Yabe et al[9]	Extending from distal part of articular disc close relation to distal radioulnar ligament having meniscus appearance	Parallel arranged collagen fibers with loose connective tissue	Fewer to more number of fibers	Higher amount of vascularity seen	Not applicable
Nandini et al 2023 (Unpublished data)	Seen attached at the triquetrum, ulnar wrist joint capsule, fifth metacarpal base and the hamate bone	Mixed tight and loosely packed parallel arranged collagen fibres	More number of elastic fibres	Rich vascularity seen	More number of nerve fibres when compared to ulno lunate ligament
Benjamin et al[10]	Surround the extensor carpi ulnaris tendon	Parallel oriented fibres with loose connective tissue	More in number	Increased blood supply	Not applicable
Chidgey et al[17]	Attached to the ulnar styloid process through its base and to the dorsal side of triquetrum	Densely packed parallel and mixed tight and loose interlaced and parallel collagen fibres	Fewer to more number of elastic fibres	More number of blood vessels seen	Not applicable

wall for the distal part of the TFCC.[9, 26] It is present in all the wrists.[2] It was postulated that the meniscus fully enclosed the prestyloid recess and some degree of variations have been seen among the wrists.[9]

Some studies found that the meniscus in almost all the wrists has been attached to the triquetrum crossing across the ulnar styloid.[11,13, 26] This attachment at the triquetrum was seen at the ulnar articular side.[11, 26] Totterman and Miller et al observed that the "meniscus homolog and extensor carpi ulnaris subsheath" were indistinct from each other[11] Fusion of meniscus with "ulnar collateral ligament and extensor carpi ulnaris sub sheath" forms the integral part of the lower lamina covering the tip of the styloid process as stated by Benjamin et al.[10] It was postulated that this whole blending of the meniscus was found on the volar side with the ulnotriqueteral ligament.[13]

Histology of the meniscus homolo

The shape of the meniscus was irregular and loose connective tissue forms its major composition.[9, 16] Rather than loose connective tissue it was found to compose of dense connective tissue by Benjamin et al. without a proper histological structure as noted by him.[10] On the contrary synovial covered fibrocartilage forms its composition.[20] Abundance of loose connective tissue along with the interposition of tight collagen bundles forms its composition.[16] He also showed that in 9 out of 11 wrists studied by him loose parallel with mixed tight collagen fibers were seen. Mixed tight and loose collagen fibers in an interlaced pattern were seen in the remaining two of the wrists.

Ulnolunate (UL) and ulnotriqueteral (UTq) ligaments

Two individual ligaments form the ulnocarpal ligament as described by three studies. They are the ulnolunate ligament having attachment at the volar part of the lunate bone and ulnotriqueteral ligament showing attachment at the volar part of the triquetrum.[2, 9, 13] In contrast, these ligaments were demonstrated as simple thickenings in the wrist capsule rather than strong unique ligament by one study.[11] These ligaments had the same attachment sites as stated by earlier studies and they form a fan-shaped attachment as described.[13] The direction was oriented more obliquely for the ulnotriqueteral ligament and the ulnolunate ligament was merged strongly with the volar radioulnar ligament.[2]

Vascularization and Innervation of the meniscus homolog

The meniscus homolog with loose connective tissue had a good amount of vascularization.[16] In most of the cases, the meniscus had free nerve endings without the presence of myelin.[15] The density was measured to be "1.9 (SE ± 0.4) for free nerve endings per mm^2, 3.1 (SE ± 1.0) for single nerve fibers per mm^2, 1.5 (SE ± 0.9) for nerve fascicles per mm^2 and 0.3 (SE ± 0.3) for perivascular neural nets per mm^2."20 The axons of the meniscus were present with Schwann cells and the bulb endings like Meissner's corpuscles and Krause's corpuscles were noted in this area. These articular corpuscles helped in the functioning of position, movement, and vibration sensation.[15]

Ulnar collateral ligament

Many studies noted that the ulnar collateral ligament was not recognized as a distinct ligamentous structure.[2, 6, 10, 12] Instead of the ulnar collateral ligament, it was termed as ulnar wrist joint capsule which merged on the ulnar styloid in its dorsal side.[2]

It was referred to as the thickened capsule of the ulnar wrist joint rather than the ulnar collateral ligament which extended from the tip of the ulnar styloid to the triquetrum and then blended with the meniscus homolog. It was described as cartilaginous thickening from the top part of the ulnar styloid which forms the proximal attachment. On the ulnar side of the triquetrum, the distal thickening of the capsule is seen as a fusion with the hyaline cartilage.[12]

Conclusion

The articular disc consisted of densely packed fibrocartilage with avascularity except in its ulnar region. Densely packed parallel or interlaced collagen fibers were seen in dorsal and volar radioulnar ligaments. The ulno-lunate, ulno-triqueteral, subsheath of the extensor carpi ulnaris tendon showed predominantly mixed tight and loose parallel collagen array. The microscopic composition of the articular disc and ulnocarpal meniscoid implies a buffering function. The tight structure and very few elastic fibers of radioulnar and ulno lunate ligaments display a central stabilizing role. The rich vascularity of the ulnocarpal meniscoid indicates the good healing potential of the structure. The subsheath of the extensor carpi ulnaris tendon prevents subluxation and dislocation of the ulnar head during mechanical functions. The anatomy of TFCC hasn't been extensively studied in the Indian population. There is no data regarding the micro-composition and vascular pattern of distribution. Hence, the study has been formulated and the outcomes of the study would serve as the much-needed data while planning arthroscopic procedures and relevant radiological observations.

The articular disc area of TFCC showed the least number of nerve fiber distribution and avascularity except in the peripheral portion of the disc.20 The epi ligaments especially the volar radioulnar ligament showed increased neuronal distribution and a good amount of arterial supply than the dorsal radioulnar ligament. The other components of TFCC like the ulno triqueteral ligament, ulnocarpal meniscoid, and sub sheath of extensor carpi ulnaris tendon showed an increased number of nerve fibers and the vascular pattern was good enough except for the ulno lunate ligament. This ulno lunate ligament rarely showed neuronal and vascular innervation. Thus this neurovascular arrangement will be of immense help in the classification of TFCC tears and its surgical repairs. The anatomy of TFCC hasn't been extensively studied in the Indian population. Even though the salience of studying the anatomy of TFCC has been well realized in the past decade, the available literature remains scarce. Hence, the study has been formulated and the outcomes of the study would serve as the much-needed data while planning arthroscopic procedures and relevant radiological observations. Avascular degeneration and nerve injury in TFCC can be possibly prevented with an unfathomable understanding of the pattern of vasculature and free nerve endings. With the availability of the above-mentioned techniques, we could study the anatomy of TFCC in a more lucid way than ever before.

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