Recent Advances in High-Resolution 3T MR Imaging of the Triangular Fibrocartilage Complex

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Disclosure statement

- None of the authors have conflicts of interest or relevant financial relationships to disclose.

- Target audience
  - Seasoned and training musculoskeletal radiologists
The triangular fibrocartilage complex (TFCC) is a complex structure which has historically been difficult to image and evaluate due to its small size and complexity.

Recent advances in magnetic resonance (MR) imaging has enabled the visualization of the TFCC with increased spatial and contrast resolution.
Purpose

- Review the optimization and routine protocol of high-resolution 3D isotropic fast-spin echo (FSE) MRI of the wrist.
- Demonstrate detailed anatomy of the TFCC and surrounding structures using these techniques with visualization of pathology and classification.
- Display how to clinically use multiplanar reformatted (MPR) images from 3D isotropic MRI.
Materials and Methods

- Wrist MRI including high-resolution 2D FSE and 3D isotropic FSE 3T images from January 2012 to June 2016.

- Review specific techniques which optimize 3T wrist imaging such as 3D Volume Isotropic Turbo Spine Echo Acquisition (VISTA) technique, Driven equilibrium (DRIVE sequence), Parallel imaging (SENSE), and oblique coronal MPR reformatting method.

- Demonstrate anatomy of the TFCC using these techniques.

- Review Palmer classification traumatic (type 1) and degenerative (type 2) lesions using the specific techniques described and treatment implications.
The diagnosis of injuries to the ligamentous structures of the wrist, especially the TFCC, has been improved with high-resolution isotropic 3D FSE imaging.

Recent advances in MR imaging include 3D VISTA, DRIVE sequence, and Parallel imaging; which combine to allow acquisition of high-resolution 3D isotropic MRI within 5-minutes scan time using a 3T magnet. This allows for increased clinical utilization of this technique.
## Routine protocols for 3T MRI wrist

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3D isotropic imaging of the wrist

- Many of the ligaments and tendons of the wrist joint are very small in size and traverse in an oblique plain to the transverse and horizontal axis of the radius acquired in conventional wrist MRI.

- 3D FSE imaging can produce quality high-resolution 3D isotropic images, however the pitfalls of this sequence are a relatively long acquisition time and image blurring.

- Techniques including driven equilibrium sequence (DRIVE), parallel imaging (SENSE), and 3D VISTA technique can therefore be used to maintain adequate signal to noise ratio in combination with a clinically feasible scan time\(^1,2\).
Known as RESTORE, FRFSE, DRIVE, T2 Plus FSE, Driven equilibrium FSE, and DEFT among numerus MR vendors.

Technique that enables a shorter scan time and improved image quality on T2-weighted imaging.

In rapid MR imaging, substances with long T1 and T2 values, such as synovial fluid, take a relatively long time for their protons to recover their longitudinal magnetization by the end of every TR interval. With a short TR, successive RF pulses occur before there is time for longitudinal relaxation to completely recover.

This eventually results in partial saturation and reduced signal from fluid.

To avoid this pitfall, a longer TR needs to be utilized in order to allow for longitudinal magnetization to recover. However, this then results in much longer scan times and saturation can still occur after many cycles.
The -90° pulse essentially “jump starts” the T1 relaxation for the next TR interval and shortens the TR by a factor of three to four.

This allows for the acquisition of high-fluid signal and consistent contrast with a relatively short TR and decreased scan times.

This technique helps provide high synovial fluid to articular cartilage contrast while preserving signal from the cartilage. It also allows a high signal-to-noise ratio of synovial fluid\textsuperscript{3,4}.

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The driven equilibrium technique applies a -90° radiofrequency (RF) pulse, which accelerates T\textsubscript{1} recovery time and accentuates signal from fluids.

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Parallel imaging

- Imaging time can be a significant limiting factor in many facets of joint imaging.

- Parallel imaging is a reconstruction technique that is utilized to decrease overall scan time while preserving spatial resolution.

- Uses the unique spatial sensitivities of each individual coil within a phased array receiver coil. This reduces sampling in the phase-encoding direction and diminishes the burden of filling lines of data with individually acquired phase gradients\(^5\).

- The end result of the acquisition technique is a decrease in scan time and decrease in the specific absorption rate, because of the reduced number of radiofrequency pulses required for transmission to the patient.
Two general approaches to parallel imaging: GRAPPA-type imaging and SENSE-type approach\textsuperscript{6}.

- **GRAPPA-type:**
  - Utilize under-sampling of k-space in the phase encoding direction.
  - Subsequent calculation of the missing portions of k-space is done using information from adjacent k-space data points and each coil sensitivity profile obtained from a separately obtained autocalibration signal.
  - Together, this results in a fully sampled k-space acquisition prior to fourier transformation.

- **SENSE-type:**
  - Reduces sampling in the phase-encoding direction by utilizing the unique spatial sensitivities of each individual coil within a phased array receiver coil.
  - This results in image aliasing. The aliased image can then be “unfolded” into an unaliased image by mathematical formulation, using the individual spatial sensitivity profiles of each receiver coil element.
Parallel imaging

- The acceleration factor (R), describes the reduced scan time parallel imaging is able to achieve\(^7\).

- The reduction in imaging time is related to the number of independent coil channels within the array.

- In principle, an 8-channel coil would be able to image eight times as fast. However, practical considerations limit the image acceleration to values below the theoretical maximum.

- Practical limitations, primarily from signal-to-noise ratio (SNR) and artifact, limit R to 1.5-3 in clinical practice with 4-12 channel phased array coils\(^8\).

Parallel imaging

- All forms of parallel imaging are subject to a reduction in signal-to-noise ratio (SNR).
  - SNR is proportional to the inverse square root of the acceleration factor R.
  - Acceleration factor of R=4, the overall SNR would be decreased by 50% compared to an image without parallel imaging.
  - This reduction of SNR can be partially offset by using high field strength magnets (3T).

- Other artifacts can be seen such as residual aliasing, ghosting, and increased noise\textsuperscript{7,8}.
3D isotropic imaging

- 3D isotropic MR imaging allows precise and detailed assessment for small joint evaluation. It has advantages for visualizing the complex anatomy of the wrist\textsuperscript{9,10}.

- **Pitfalls** of isotropic 3D MR imaging
  - Imaging blur.
  - Slight image degradation after reformatting.
    - Although, this has not shown to affect delineation of small structures of the wrist, including the intrinsic ligaments and TFCC.
Advantages

- Cross-sectional imaging may be reformatted into an arbitrary plane without clinically significant degradation of image quality\(^\text{10}\).

- Ability to cross-link between multiple planes allows for complete evaluation of very small structures and lesions, without risk of misregistration.

- Thin contiguous sections reduce partial volume artifact.

- Potential to lower overall acquisition time by using a single isotropic 3D sequence versus three (axial, coronal, and sagittal) 2D sequences.
3D isotropic imaging

Disadvantages

- Longer acquisition time to obtain 3D isotropic imaging.
- Gradient echo type 3D imaging is faster but has lower contrast resolution.
  - Spin echo sequencing has increased contrast, especially in regard to bone marrow and soft-tissue edema.
- Fast spin echo (FSE) with long echo train length (ETL) can decrease acquisition time. Also, using techniques such as parallel imaging and driven equilibrium technique can optimize imaging and decrease scan time.
3D isotropic imaging

Image optimization

- Slice thickness/voxel size vs. scan time
- Effect of echo train length (ETL)
  - Increased ETL leads to imaging blur
- Slice thickness vs. ETL
- Driven equilibrium technique
- Parallel imaging technique
Increase in slice thickness/voxel size resulted in decreased scan time, but also caused significant increase in image blur.

Slice thickness/voxel size should be less than or equal to 0.4mm when ETL = 66.
Decrease in ETL improves imaging blur
Thinner slice/smaller voxel images demonstrate less image blur in the same scan time.
Result of high-resolution 3D isotropic MRI image optimization

PDWI w/wo FS, 0.33 x 0.33 x 0.33 mm, FOV 90 mm
TR/TE = 1400/29, 150 slices, Scan time = 7 mins 14 sec
Example of the use of 3D imaging to localize targeted structures for complete evaluation.
TFCC anatomy

- Ulnolunate ligament
- Ulnotriquetral ligament
- Extensor carpi ulnaris tendon sheath
- Meniscus homologue
- Ulnar collateral ligament
- Triangular ligament (distal lamina)
- Disc proper (Articular disc)
- Ligamentum subcruentum
- Triangular ligament (proximal lamina)
Composed of:
- Articular disc (disc proper)
- Dorsal and volar radioulnar ligaments
- Meniscus homologue
- Ulnar collateral ligament (UCL)
- Sheath of the extensor carpi ulnaris (ECU)
- Ulnocarpal ligamentous complex:
  - Ulnolunate ligament
  - Ulnotriquetral ligament
  - Ulnocapitate ligament

Three major functions:\footnote{11}
- Major stabilizer of the distal radioulnar joint.
- Ulnar stabilizer of the radio-ulno-carpal joint.
- Functions as cushioning for the ulnar carpus and carries a large portion of the forearm axial load.
The triangular fibrocartilage (TFC) is the largest component of the TFCC.

- Composed of:
  - Fibrocartilage disc
  - Dorsal and volar radioulnar ligaments

- At the ulnar attachment it usually bifurcates into a proximal and distal lamina that can be visualized on coronal and oblique coronal MR imaging.

- The “triangular ligament” is a synonym for the ulnar aspect of the TFC.

- There is fibrovascular connective tissue named the “ligamentum subcruentum” between the two laminae, which is normally hyperintense on fluid-sensitive sequences because of rich vascularity\(^ {12,13} \).

Oblique coronal 3D MPR on 3T image displaying the ulnar attachment of the triangular fibrocartilage (triangular ligament). The distal lamina inserts to the tip of the ulnar styloid process (blue arrow). The proximal lamina inserts to the fovea of the ulnar styloid process (green arrow). The region of high signal intensity between the two lamina shows the ligamentum subcruentum (yellow arrow).
The radioulnar ligament radial attachment has fibers that travel from the volar and dorsal aspects of the sigmoid notch bony surface to the base of the ulnar styloid process.

- Dorsal radioulnar ligament
- Volar (palmar) radioulnar ligament

The central disc inserts directly to the hyaline cartilage of the sigmoid notch.

TFC and radioulnar ligaments on isotropic 3D coronal fat suppressed PD images. The dorsal radioulnar ligament (green arrow), the central disc (white arrow), and the volar radioulnar ligament (blue arrow) are visualized. The meniscus homologue (orange arrow) merges from the tip of the ulnar styloid process and inserts on the lunar side of the triquetrum and lunate. L, lunate; T, triquetrum; R, radius; U, ulna.
Ulnocarpal ligamentous complex (UCLC)

The ulnolunate ligament on isotropic 3D coronal fat suppressed PD-weighted image (a), and on 2D sagittal PD-weighted image (b). The ulnolunate ligament shows low intensity (white arrows). L, lunate; R, radius.

The ulnotriquetral ligament on isotropic 3D coronal fat suppressed PD-weighted image (a), and on 2D sagittal PD-weighted image (b). The ulnotriquetral ligament shows low intensity (green arrows). L, lunate; T, triquetrum; R, radius; P, pisiform.
The **UCL** is a thin fibrous ligament that lies immediately superficial to the meniscus homologue.

It is controversial whether the UCL actually exists; many consider this structure as the ulnar capsule rather than a distinct structure.

In most cases, it blends seamlessly with the ECU subsheath and the meniscus homologue.

This is best assessed on high-resolution coronal or oblique coronal MR images.
Palmer classification for TFCC injury

- **Class 1** Traumatic
  - A Central perforation
  - B Ulnar avulsion
  - C Distal avulsion
  - D Radial avulsion

- **Class 2** Degenerative
  - A Partial thickness thinning of the articular disc
  - B A + chondral degeneration of lunate and/or ulnar head
  - C B + full thickness tear of the articular disc
  - D C + Partial tear of the lunotriquetral ligament
  - E D + Full tear of the lunotriquetral ligament and arthrosis
Traumatic and degenerative lesions of the TFCC

- The injury of the TFCC is a well-recognized cause of ulnar-sided wrist pain.

- The palmar classification categorizes lesions as traumatic (type 1) or degenerative (type 2).
  - Used by hand surgeons to determine mechanism of injury and directing clinical management.

- Degenerative injuries are far more common.
  - Result from repetitive loading of the ulnar aspect of the wrist.
  - Ulnar impaction syndrome.

- Traumatic injuries:
  - Most commonly result from fall on pronated outstretched hand with axial loading force or hyperpronation injury of the forearm.
  - More common at the periphery of the TFCC.
Class 1A lesion

- Focal traumatic tear or perforation of the central disc approximately 2-3 mm medial to the radial attachment.
- The avascular articular disc has limited healing capacity; therefore debridement is the usual surgical treatment of choice.

TFCC central perforation. There is a focal defect in the central disc (orange arrows).
Class 1B lesion

- **Traumatic avulsions** of the TFCC from insertion to the ulnar fovea and styloid process.
- Often associated with fracture at the base of ulnar styloid.
- Associated with **distal radioulnar joint instability** (TFCC is a major stabilizer of DRUJ).
- Surgical repair attempted either arthroscopically or using open technique.
  - Arthroscopic techniques is becoming more common and minimize complications such as extra incisions, suture knots, skin problems, and septic arthritis from button and sutures.
  - Approximately 74% achieve “good to excellent” results with reduction in pain, and improved grip strength\textsuperscript{15}.

Ulnar attachment tear of the TFCC. Images shows traumatic avulsion of the TFCC from its insertion on the ulnar fovea (orange arrows).
Class 1B lesion

MPR axial arthrogram image with green reference line. Oblique coronal MPR showing an example of how small tears can be non-visualized (blue arrow). Although, using the isotropic images, the ulnar attachment avulsion is clearly seen on the second acquired MPR oblique image (orange arrow).
Class 1C lesion

- Class 1C lesions represent traumatic tears of the TFCC in its periphery, specifically involving the ulnolunate or ulnotriquetral ligaments.
  - Can result in ulnocarpal instability with palmar translocation of the ulnar carpus in relation to the radius and/or ulnar head.
  - Small tears: arthroscopic repair. Large tears: often open procedure is used.
  - Repair can be augmented using a portion of the flexor carpi ulnaris tendon\(^\text{16}\).

A traumatic tear of the TFCC specifically involving the ulnotriquetral ligaments (Class 1C) and with degenerative thinning of the central disc without perforation (Class 2A). Images demonstrate the ulnotriquetral ligament tear (orange arrows) and thinning of the central disc (blue arrows).
Class 1D lesion

- Traumatic avulsion of the TFCC from its radial attachment at the distal aspect of the sigmoid notch.
- Injuries can be accompanied by distal radial fractures.
- Studies on debridement report good results approximately 80% of the time.

TFCC radial attachment tear of the central disc with complete disruption (orange arrows) and laxity.
Class 2A-2E lesions (degenerative)

- **Class 2A lesions** represent degenerative wear or thinning of central disc without perforation.

- **Class 2B lesions** represent degenerative wear of the central disc with additional chondral degeneration of the lunate and/or ulna.

- **Class 2C lesions** represent perforation of the central disc with chondral degeneration seen in Class 2B.
  - All three above treated with conservative therapy first.
  - If conservative fails, ulnocarpal unloading performed with ulnar shortening procedure.

- **Class 2D lesions** represent further progression of degenerative changes with lunotriquetral ligament disruption and findings seen in class 2C.
  - Debridement of the TFCC and lunotriquetral ligament, chondroplasty, and fixation of the lunotriquetral interval if unstable and/or ulnar shortening.

- **Class 2E lesions** represent final stages of ulnar impaction syndrome with large central disc perforation, chondral degeneration, and lunotriquetral ligament disruption.
  - Hemiresection arthroplasty salvage procedures (Darrach or Sauve-Kapandji procedures)
Degeneration with perforation of the central disc (orange arrows), chondral degeneration of the lunate and/or ulna (*), and lunotriquetral ligament disruption (blue arrow).
MR arthrogram images displaying degeneration with perforation of the central disc of the TFCC (orange arrows), chondral degeneration of the lunate and/or ulna, and lunotriquetral ligament (LTL) perforation, consistent with a Palmer Class 2D lesion.

These arthrographic images show chondral degeneration of the lunate with a small cartilage flap (white arrow).

They also show a small and irregularly shaped LTL with oblique linear high signal (contrast) through its membranous portions (blue arrows).

Intra-articular contrast extends into the midcarpal joint (green arrow), suggesting a LTL perforation.
Recent advances in MRI has enabled the visualization of the TFCC with increased spatial and contrast resolution.

These advances include 3D-isotropic imaging, parallel imaging, DRIVE sequence, and adjustment of the ETL and slice thickness/voxel size for optimal imaging.

With these techniques we achieve greater appreciation of the very small anatomical structures involving the TFCC, which allows for improved evaluation and classification of the TFCC injuries. This ultimately gives the surgeon more information for their treatment decision making.
References


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