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In Vivo 7.0-Tesla Magnetic Resonance Imaging of the Wrist and Hand: Technical Aspects and Applications

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Abstract

Magnetic resonance imaging (MRI) at 7.0 T has the potential for higher signal-to-noise ratio (SNR), improved spectral resolution, and faster imaging compared with 1.5-T and 3.0-T MR systems. This is especially interesting for challenging imaging regions like the wrist and the hand because of the small size of the visualized anatomical structures; the increase in SNR could then be directly converted into higher spatial resolution of the images. Practically, imaging at 7.0 T poses a variety of technical challenges such as static (B_0) and radiofrequency (B_1) homogeneities, shimming, chemical shift artifacts, susceptibility artifacts, alterations in tissue contrast, specific absorption rate limitations, coil construction, and pulse sequence tuning. Despite these limitations, this first experience in anatomical imaging of the wrist and the hand at 7.0 T is very promising. Functional imaging techniques will gain importance at ultra-high-field MRI and need to be assessed in detail in the future.

Keywords

Wrist; hand; MRI; 7 Tesla; ultra-high-field MRI

In recent years, several musculoskeletal magnetic resonance imaging (MRI) studies have ventured to the higher field strength of 3.0 T from the clinical standard of 1.5 T. Translation to higher magnetic field strength is motivated by signal-to-noise ratio (SNR) improvement in the MR image, which in turn allows an increased spatial resolution but is also fraught with technical challenges.^{1,2} This is even truer for ultra-high-field (7.0 T) MR scanners, which have been predominantly used for research purposes until now. The wrist is an especially challenging region because of the small size of the relevant anatomical structures such as intrinsic and extrinsic ligaments, articular cartilage, and triangular fibrocartilage complex (TFCC). Ultra-high-field MR therefore is expected to improve diagnostic imaging possibilities.³ Initial experiences at 7.0T MRI are summarized briefly in this article.

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Technical Aspects

MR Scanner and Radiofrequency Coil

Currently, there are ~30 7.0-T whole-body MR scanners operating around the world; all those scanners are used for research purposes. The expectations on improved morphological, structural, as well as functional imaging of human subjects in general and musculoskeletal applications in particular at ultra-high-field strength are high; however, several technical challenges have to be faced before the benefits of 7.0-T MR systems can be totally utilized.

Although theoretically SNR increases linearly with static magnetic field (B_0), specialized radiofrequency (RF) coils are required to achieve such potential. At ultra-high fields, the interactions between RF coils and biological tissues become more complex due to high electrical conductivity and low dielectric constant. These circumstances result in significant engineering challenges for novel and innovative RF coil design for maintaining B_1 homogeneity. One of the greatest technical challenges for imaging at 7.0 T is the lack of commercially available dedicated RF coils. Transmit/receive RF coils have many advantages over receive only phased array coils in terms of image quality and improved uniformity of the local imaging field. They are also critical for managing RF energy considerations at 7.0 T. The use of local transmit coils reduces the amount of RF required for imaging of small joints to negligible levels that are well within the regulatory limitations for specific absorption rates (SARs). This results in more efficient imaging, allowing more slices per acquisition than comparable examinations performed with receive only coils.

Ashman et al reported a custom-designed dedicated wrist coil with an inner diameter of 12 cm, which they used at an 8.0-T magnet.³ They postulated that the SNR of their images would have been even higher if a dedicated phased array coil had been available.

At our institution we use an in-house-built RF coil that was originally designed for imaging the carotid arteries. The RF coil consists of two curved “clamshell” sections. Each section has an inner layer with four overlapped 48-mm circular receive coils, and an outer layer 15 mm above that with two 70-mm-square overlapped transmit loop coils, making a total of eight receive and four transmit elements. Transmit power is split into four equal parts by a cascade of Wilkinson dividers and applied to the transmit loops with a birdcage-like phase relationship. Applied as a wrist coil, the two clamshell sections are placed face to face with the wrist in between (Fig. 1).

The use of multielement RF coils provides the opportunity to use parallel imaging techniques and to decrease acquisition times substantially.^{4–6}

Magnet field homogeneity and shimming are even more an issue than on 3.0-T scanners. Increased chemical shift differences between water and fat resonant frequencies also significantly influence image quality at 7.0 T. Adjustment of the receiver bandwidth (BW) can reduce the so-called chemical shift artifacts (Fig. 2), but this has to be traded off for a loss of signal intensity. However, the increased chemical shift differences between water and fat at ultra-high fields can also be used; a recent study has shown that it might be used for optimized fat suppression purposes⁷ or spectroscopy applications.⁸

Another important issue at 7.0 T is that the regulatory limitations for specific SARs should not be exceeded, although RF power deposition is much higher than at 1.5 T or 3.0 T, due to its quadratic dependence on B_0 ; this is especially true for high-duty RF pulse sequences in three-dimensional (3D) mode. It was shown that practically the increase in the RF power requirement is not as steep as expected from the theoretical model.^{9–11} However, this still represents a significant restriction for many heavy-duty-cycle RF pulse sequences,

particularly those that rely on multiple refocusing RF pulses as well as RF-intensive pulse sequences, such as the inversion recovery sequence, magnetization transfer, and spin-lock techniques.¹²

Furthermore, the relaxation characteristics of tissues are dependent on B_0 ; taking this into account, the repetition (TR) and echo times (TE) have to be adapted to optimize SNR and contrast.¹²

Pulse Sequences

Theoretically, nearly all of the pulse sequences available for lower field strength systems can be used at 7.0 T, but ongoing studies will have to optimize the pulse sequences or even modify the pulse sequences to cope with SAR limitations.

Studies at 1.5 T and 3.0 T have used several different sequences to image all important structures of the wrist.^{13–15} We aimed to transfer some of these sequences to 7.0 T, including a coronal and axial 3D gradient-echo (GRE) MR sequence (FLASH) with and without fat suppression; a coronal, axial, and sagittal proton-density (PD)-weighted turbo spin-echo (TSE) MR sequences with and without fat suppression; and another 3D GRE-based MR sequence (MEDIC) with isotropic voxel size. The sequences were tuned to acquired high-resolution images resulting in a maximum in-plane resolution of $0.078 \times 0.078 \text{ mm}^2$ with slice thickness of 2 mm for the coronal T1-weighted TSE sequence (Fig. 2) and $0.176 \times 0.176 \text{ mm}^2$ with 0.5 mm slice thickness for the axial 3D FLASH sequence used for the high-resolution trabecular bone imaging of the distal radius. Due to the improved coil design, we therefore ended up in a higher in-plane resolution than previously reported at 8.0 T.³ Lenk et al compared several MR imaging sequences at clinical scanners (1.5 T/3.0 T) for the wrist and found that the 2D and 3D MEDIC yielded the best image quality and carpal ligament/TFCC detection rates.¹⁴ The 3D MEDIC they used had an isotropic resolution of $0.33 \times 0.33 \times 0.33 \text{ mm}^3$ and was acquired within 6 minutes and 47 seconds. We also set up a 3D MEDIC for 7.0 T resulting in an almost isotropic resolution of $0.35 \times 0.35 \times 0.40 \text{ mm}^3$ and an acquisition time of 7 minutes and 50 seconds. The difference in the acquisition time is most likely due to the fact that we acquired more slices; however, a direct comparison is not possible because the number of acquired slices was not given for the 3.0-T study. The isotropic 3D MEDIC allows multiplanar 3D image reconstruction without a loss of image quality as shown on the 7.0-T images in Fig. 3.

Applications

Anatomy

MRI at 7.0 T offers the opportunity to acquire high-resolution images of the wrist showing extensive anatomical detail.

The Triangular Fibrocartilage Complex—The TFCC is a fibrocartilage-ligament complex, connecting the ulnar aspect of the carpus to the ulna, and consists of the triangular fibrocartilage proper, dorsal and volar radioulnar ligaments, ulnolunate ligament, ulnotriquetral ligament, the proximal ligamentous component (also called triangular ligament), ulnar collateral ligament, meniscal homologue, and extensor carpi ulnaris (ECU) tendon sheath. The TFCC stabilizes the distal radioulnar joint, translates and diffuses forces from the wrist to the ulna, and stabilizes the lunate within the medial facet of the radial articular surface.¹⁶

At 1.5 T and 3.0 T MRI, the normal triangular fibrocartilage proper appears as a thick band of low signal intensity with all pulse sequences. At 7.0 T MRI, higher signal intensities may be observed in the triangular fibrocartilage proper in a healthy population on GRE sequences

(Fig. 4). The ulnar attachment of the triangular ligament is conspicuous and separable from hyaline cartilage due to its higher signal intensity and striated appearance (Fig. 5) at 7.0 T. Thus high-resolution images acquired at 7.0 T—as shown in Fig. 5—clearly depict the components of the TFCC in detail and might be useful to solve uncertain cases of pathological conditions in the future.

The Ligaments—Despite their small size, the carpal and finger ligaments can be visualized on high-resolution images obtained at 7.0 T with great detail, thus improving the diagnostic accuracy.

Two types of ligaments can be differentiated in the wrist: extrinsic and intrinsic ligaments. The extrinsic ligaments connect the carpal bones to the radius, ulna, and metacarpal bones, and the intrinsic ligaments bind the individual carpal bones and act to restrict motion between the carpal bones.

A large number of different ligaments with variable nomenclature have been described, especially on the volar side of the wrist.^{17–19} The most important of these ligaments are the radioscaphocapitate, the short and long radiolunate, and the volar deltoid. The latter is composed of the triquetrocipitate (Fig. 6A) and the scaphocapitate ligament; those two connect the capitate to the triquetrum and to the scaphoid.

The two main ligaments on the dorsal side of the wrist are the dorsal intercarpal ligament and dorsal radiotriquetral ligament (Fig. 6B); these form a “V” with the apex pointing toward the triquetrum. The dorsal radiotriquetral ligament connects the distal radius to the scaphoid, lunate, and triquetrum, and the dorsal intercarpal ligament connects the scaphoid, capitate, lunate, and triquetrum.

The radial collateral ligament extends from the tip of the radial styloid process to the scaphoid and trapezium. The ulnar collateral ligament is a connective tissue cord that runs from the ulnar styloid process and below the base of the pisiform to the adjacent medial part of the flexor retinaculum.

The scapholunate ligament (SLL; Fig. 7A) and the lunotriquetral ligament (LTL; Fig. 7B) are the most important intrinsic ligaments of the wrist. These ligaments tend to be C-shaped and are thicker dorsally and ventrally. The central portion is membranous. The proximal zones of the SLL and LTL are the weakest parts of the ligaments, inserting directly on the hyaline cartilage of the scaphoid, lunate, and triquetral bones, whereas the dorsal and volar components often insert directly on the carpal bones. The integrity of the intrinsic and extrinsic ligaments is critical for the maintenance of carpal stability.

In the metacarpophalangeal and interphalangeal joints, the bones are bound together by collateral and palmar ligaments. The palmar ligaments are dense firm bands of fibrocartilaginous tissue spreading at the sides to merge with the collateral ligament fibers. The collateral ligaments are strong cords attaching proximally to depressions on the condylar heads and spreading distally to the palmar aspect of the base of the phalanges.¹⁹

The Median and the Ulnar Nerve—The median nerve transverses the wrist through the carpal tunnel, a space bordered by the carpal bones and flexor retinaculum. There the nerve runs together with the eight tendons of flexor digitorum profundus and flexor digitorum superficialis and one flexor pollicis longus tendon; it courses superficial to the flexor digitorum superficialis muscle proximal to the carpal tunnel and parallel to the second and third flexor digitorum superficialis tendons within the carpal tunnel (Fig. 8A,B). In the palm, it gives off its five final branches: the radial branch innervating the thenar muscles, and four

sensory branches for the first, second, third, and the radial half of the fourth digit. A compression of the median nerve at the carpal tunnel is the most common peripheral nerve entrapment syndrome, causing the so-called carpal tunnel syndrome.

The ulnar nerve passes the wrist through a fibroosseous tunnel known as Guyon's canal, which is a possible site of ulnar nerve compression (Fig. 8A). This tunnel extends from the volar carpal ligament at the proximal edge of the pisiform to the origin of the hypothenar muscles at the level of the hamulus. The floor of this tunnel is composed of the pisiform, hamate, flexor retinaculum, and hypothenar muscle; its roof is composed of the volar carpal ligament, palmaris brevis muscle, and fibers of the palmar fascia. The ulnar nerve transverses this space together with the ulnar artery and communicating veins, and it divides into the superficial sensory nerve and the deep motor nerve. The latter innervates the palmaris brevis, hypothenar muscle, lateral lumbrical and interosseous muscle, adductor pollicis, and abductor digiti minimi muscles.

The Tendons—The tendons of the wrist are grouped into flexor and extensor compartments (Fig. 8).

The flexor tendons are located on the volar aspect of the wrist. The flexor pollicis longus runs dorsal and lateral to the median nerve. The flexor digitorum superficialis and profundus tendons are located medial to the median nerve. The flexor carpi radialis tendon passes outside the carpal tunnel, coursing just lateral to the tunnel, and inserts on the base of the second metacarpal bone. The flexor carpi ulnaris tendon can be found medial to the ulnar nerve and inserts on the pisiform, the hamulus, and the base of the fourth and fifth metacarpal bones.

The extensor tendons lie superficial to the carpal bones and interosseous ligaments and are subdivided into six compartments: The first compartment is located lateral to the distal radius and contains the abductor pollicis longus and extensor pollicis brevis tendons. The second compartment is located lateral to Lister's tubercle, an osseous protuberance on the dorsal distal radius, and contains the extensor carpi radialis brevis and longus tendons. The tendons of the first and second compartments are frequently involved in injuries caused by a fall on the outstretched hand. The third compartment is located medial to Lister's tubercle and contains the extensor pollicis longus tendon. The extensor indicis proprius and extensor digitorum communis tendons are referred to as the content of the fourth extensor compartment, whereas the extensor digiti minimi tendon is attributed to the fifth compartment. Finally, the sixth compartment, located medial to the ulnar styloid, contains the extensor carpi ulnaris tendon and also is frequently injured during wrist trauma.

The flexor tendons of the hand (Fig. 9) are held in place in the digits by fibrous sheaths that attach along the borders of the proximal and middle phalanges, to the interphalangeal joint capsules, and to the surface of the distal phalanx; these attachments form semicylindrical tunnels that allow the passage of tendons. Additionally, there are transversely oriented thickened connective tissue bands across the shafts of the proximal and middle phalanges that are referred to as the pulley system of the fingers.

The extensor tendons of the hand (Fig. 9) arise from a common compartment in the dorsum of the wrist, running underneath the extensor retinaculum. Over the dorsum of the proximal interphalangeal joint, the extensor tendon divides into three slips: The central slip is broad and inserts on the dorsal aspect of the middle phalanx; the two lateral slips merge with fibers of the tendons of the lumbrical muscles on the radial side and the interosseous tendons on both sides; finally they converge into a common band that inserts on the dorsal aspect of the distal phalanx.

The Bones—The diagnosis of osteoporosis is based on the quantification of bone mineral density (BMD) by dual-energy x-ray absorptiometry (DEXA) techniques. Because osteoporosis affects not only the BMD but also the trabecular bone microarchitecture,²⁰ BMD is not sufficiently comprehensive to characterize trabecular bone deterioration completely.²¹

Therefore direct visualization and assessment of the micro-architecture by high-resolution imaging in conjunction with image processing is important to evaluate the topological changes that accompany bone loss and treatment. In vivo and noninvasively, this can be accomplished by MRI of the distal radius.²² However, at 3.0 T, its in-plane spatial resolution was still hampered by SNR constraints.²² MRI at 7.0 T might be able to improve those results, due to the overall higher signal. We have acquired a high-resolution MRI data set of the distal radius with an in-plane resolution of $0.176 \times 0.176 \text{ mm}^2$ and a slice thickness of 0.5 mm (Fig. 10).

The Cartilage—The hyaline cartilage within the wrist and the fingers normally measures 0.5 to 1.0 mm maximum. Nevertheless, it can be appreciated as a high-signal intensity structure on 3D FLASH images at 7.0 T, which even delineate the interface between apposing cartilages as a low-signal intensity band (Fig. 4).

Biochemical Imaging

7.0 T MRI is expected to generate more than just morphological imaging. Potential molecular/functional imaging techniques include spectroscopy, sodium imaging, delayed gadolinium-enhanced MRI of cartilage (dGEMRIC), T_2 , T_2^* mapping, and T_1 . All those techniques significantly benefit from the signal-to-noise gains at increased field strengths.^{23,24}

dGEMRIC T_1 mapping, which is determined by the gadopentetate dimeglumine (Gd-DTPA(2-)) concentration, has become a specific measure of tissue proteoglycan concentration. Williams et al have been using the dGEMRIC technique for functional imaging of the first carpometacarpal joint at 1.5 T.²⁵ They summarized that dGEMRIC T_1 mapping of cartilage in the first carpometacarpal joint was technically feasible and demonstrated differences between cartilage in asymptomatic and osteoarthritis patient joints. dGEMRIC T_1 mapping has already been performed at 7.0 T,²⁶ but to our knowledge not yet at the wrist or hand.

Another promising method for measuring proteoglycan content is sodium MR imaging, which provides maps of proteoglycan content in cartilage. Sodium MR imaging of the wrist has potential for depicting early degeneration associated with osteoarthritis and has been performed by Borthakur et al at 4.0 T.²⁷ Up to now sodium imaging has not been applied on the wrist on 7.0 T, but it is believed to be a powerful technique.

T_1 imaging probes the interaction between motionally restricted water molecules and their macromolecular environment.²⁸ Previous studies have successfully quantified T_1 relaxation time in femorotibial cartilage; the T_1 relaxation time is inversely correlated with proteoglycan content.²⁸ Akella et al^{28a} were the first to perform T_1 MR imaging of the wrist. They demonstrated the feasibility of T_1 wrist imaging and postulated that it may provide better definition of cartilage lesions and accurate quantitation of small changes in cartilage degeneration. 7.0 T studies using T_1 for imaging of the wrist have not been done so far.

T_2 relaxation is considered a reliable and validated method for the assessment of the collagen ultrastructure of articular cartilage.²⁹ Cartilage T_2 reflects the interaction of water and the extracellular matrix on a molecular level, particularly changes in water and collagen

content and tissue anisotropy. Recently, we demonstrated that in vivo T_2 mapping of cartilage in the wrist is feasible at 7.0 T (Fig. 11). Future patient studies are necessary to assess the value of this method in detail. Gambarota et al investigated the T_2 relaxation time in human median nerve at 7.0 T, suggesting that T_2 mapping in the future might help in detecting and investigating diseases of the peripheral nervous system, such as compressive and inflammatory neuropathies.³⁰

Other biochemical imaging techniques that have not been used on the wrist but have a high potential to play a major role in the future due to ultra-high-field MR systems include magnetic resonance spectroscopy (MRS), magnetization transfer (MT), diffusion-weighted imaging (DWI), and perfusion techniques.

MRS was demonstrated on skeletal muscle^{31,32} and can be used for tumor characterization;³³ it is also feasible to image the phosphorus distribution in bone, which might be used for bone densitometry in the future.³⁴

MT refers to the magnetic coupling of spin states from macromolecular compartments with those of bulk free water through exchange processes and was reported to be sensitive to changes in the collagen network of cartilage.³⁵

DWI exploits the random translation motion of water protons in a biological tissue, which reflects tissuespecific diffusion capacities and can be used for tissue characterization. DWI was shown to provide valid information about cartilage structure and biochemical composition due to diffusion restriction caused by collagen fibers and proteoglycans.^{36,37}

The blood oxygenation level detection (BOLD) imaging concept is based on the changes in susceptibility between oxyhemoglobin and deoxyhemoglobin and has been used for brain mapping so far.³⁸ In the future it might be used for the observation of in vivo perfusion changes in muscle.³⁴

Conclusion

7.0 T MRI has great potential for musculoskeletal applications in general and imaging of the wrist and the hand in particular. High-resolution images can be acquired that could significantly improve diagnostic confidence and accuracy. The use of an appropriate RF coil design is the most essential element in obtaining high-quality images of the small joints of the hand and wrist at 7.0 T. Functional imaging techniques will gain importance in the future, adding further valuable information to the high-resolution 7.0-T images. However, further studies are needed to assess the feasibility and the clinical value of these new methods in detail.

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Figure 1.
In-house-constructed four-channel transmit and eight-channel receive coil formed as two separate concave parts that can be placed on the volar and dorsal aspects of the wrist or hand.

Figure 2.

Details of coronal turbo spin-echo T1-weighted magnetic resonance images (TR/TE, 500 ms/15 ms; resolution, $0.08 \times 0.08 \times 2 \text{ mm}^3$; number of slices, 8; acquisition time, 5 minutes, 33 seconds) of the wrist acquired with different bandwidths. (A) 75 Hz/pixel. (B) 130 Hz/pixel. (C) 170 Hz/pixel. Chemical shift artifacts were measured at the proximal aspect of the lunate: 5.0 mm at a bandwidth of 75 Hz/pixel, 3.2 mm at a bandwidth of 130 Hz/pixel, and 2.7 mm at a bandwidth of 170 Hz/pixel. The decrease in chemical shift artifacts with increasing bandwidth is appreciated.

Figure 3. (A) Isotropic coronal 3D MEDIC magnetic resonance images (TR/TE, 58 ms/24 ms; resolution, $0.35 \times 0.35 \times 0.4 \text{ mm}^3$; number of slices, 80; acquisition time, 7 minutes, 50 seconds) of the fingers in a healthy volunteer with (B) sagittal and (C) axial reconstructions.

Figure 4.

Coronal 3D FLASH magnetic resonance image (TR/TE, 20 ms/5 ms; resolution, $0.20 \times 0.20 \times 1 \text{ mm}^3$; number of slices, 44; acquisition time, 3 minutes, 11 seconds) of the wrist with fat suppression in a healthy volunteer. The cartilage of each of the carpal bones can be clearly delineated; even cartilage surfaces facing each other can be differentiated. Also note one of the carpometacarpal ligaments marked with an arrow. The triangular fibrocartilaginous complex (arrowhead) shows high signal intensity on this gradient-recalled echo image.

Figure 5.

Details of three coronal turbo spin-echo proton-density-weighted magnetic resonance images (TR/TE, 3000 ms/15 ms; resolution, $0.22 \times 0.22 \times 2 \text{ mm}^3$; number of slices, 20; acquisition time, 3 minutes, 9 seconds) of the wrist with fat suppression in a healthy volunteer. Components of the triangular fibrocartilaginous complex can be seen. (A-C) the triangular fibrocartilage proper (arrows), (A, B) the triangular ligament (asterisk), and (C) the ulnolunate ligament (arrowheads).

Figure 6.

(A) Coronal 3D FLASH magnetic resonance (MR) image (TR/TE, 20 ms/5 ms; resolution, $0.20 \times 0.20 \times 1 \text{ mm}^3$; number of slices, 44; acquisition time, 3 minutes, 11 seconds) of the wrist with fat suppression in a healthy volunteer. Extrinsic volar carpal ligaments can be appreciated: radioscaphocapitate ligament (short arrow), long radiolunate ligament (arrowhead), and triquetrocapitate ligament (long arrow). Tm, trapezium; S, scaphoid; L, lunate; T, triquetrum; R, radius; U, ulna. (B) Corona turbo spin-echo proton-density-weighted MR image (TR/TE, 3000 ms/15 ms; resolution, $0.22 \times 0.22 \times 2 \text{ mm}^3$; number of slices, 20; acquisition time, 3 minutes, 9 seconds) of the wrist with fat suppression in a healthy volunteer. Extrinsic dorsal carpal ligaments are shown: dorsal intercarpal ligament (arrows), dorsal radiotriquetral ligament (arrowheads).

Figure 7.

Coronal turbo spin-echo proton-density-weighted magnetic resonance images (TR/TE, 3000 ms/15 ms; resolution, $0.22 \times 0.22 \times 2 \text{ mm}^3$; number of slices, 20; acquisition time, 3 minutes, 9 seconds) of the wrist with fat suppression in a healthy volunteer. Intrinsic carpal ligaments can be appreciated. (A) Scapholunate ligament (arrow), and (B) lunotriquetral ligament (arrowhead).

Figure 8.

(A) Axial turbo spin-echo proton-density-weighted magnetic resonance (MR) images (TR/TE, 3000 ms/15 ms; resolution, $0.22 \times 0.22 \times 2 \text{ mm}^3$; number of slices, 20; acquisition time, 3 minutes, 9 seconds) and (B) coronal 3D MEDIC; TR/TE, 58 ms/24 ms; resolution, $0.35 \times 0.35 \times 0.4 \text{ mm}^3$; number of slices, 80; acquisition time, 7 minutes, 50 seconds). MR images of the wrist in a healthy volunteer showing the median nerve (arrowheads) right next to the flexor tendons (F) and the ulnar vessels and nerve (circle). One of the extensor tendons is marked with an E. T, thenar muscles; H, hypothenar muscles.

Figure 9.

Magnetic resonance images of the fingers in a healthy volunteer. (A) Axial 3D FLASH image (TR/TE, 20 ms/5 ms; resolution, $0.18 \times 0.18 \times 1 \text{ mm}^3$; number of slices, 72; acquisition time, 3 minutes, 3 seconds) at the bases of the proximal phalanx III and IV. (B) Axial proton-density (PD)-weighted turbo spin-echo (TSE) image (TR/TE, 3460 ms/15 ms; resolution, $0.16 \times 0.16 \times 2 \text{ mm}^3$; number of slices, 30; acquisition time, 1 minute, 47 seconds) at the diaphysis of the proximal phalanx II and III. (C) Axial 3D FLASH image at the diaphysis of the middle phalanx II and III. (D) Sagittal PD-weighted TSE image (TR/TE, 3000 ms/15 ms; resolution, $0.25 \times 0.25 \times 2 \text{ mm}^3$; number of slices, 30; acquisition time, 1 minutes, 47 seconds) at the midline of the fourth digit. B, corpus phalanges; white arrowheads, tendon of deep flexor digitorum muscle; black arrowheads, tendons of superficial flexor digitorum muscle; arrows, tendon of extensor digitorum muscle/dorsal aponeurosis; circles, proper digital palmar arteries, veins, and nerves. d, distal phalanx; m, middle phalanx; p, proximal phalanx.

Figure 10. Axial 3D FLASH magnetic resonance image (TR/TE, 20 ms/4.7 ms; resolution, $0.18 \times 0.18 \times 0.5 \text{ mm}^3$; number of slices, 52; acquisition time, 2 minutes, 52 seconds) of the wrist in a healthy volunteer being used for calculating quality parameters of the trabecular bone structure in the distal radius (R) and ulnar (U).

Figure 11.

T2 mapping of cartilage in the wrist of a healthy volunteer using a fat-suppressed multiecho spin-echo sequence (TR/TEs, 3000 ms/16.5 ms, 33.0 ms, 49.5 ms, 66.0 ms, and 82.5 ms; resolution, $0.39 \times 0.39 \times 1 \text{ mm}^3$; acquisition time, 6 minutes, 22 seconds) at 7.0 T.