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High-Resolution Interleaved Water-Fat MR Imaging of Finger Joints with Chemical-Shift Elimination

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Abstract

Purpose—To study the use of an interleaved water-fat (IWF) sequence with a custom-made RF coil for high-resolution imaging of arthritic finger joints.

Materials and Methods—High-resolution finger MRI was performed using a custom-made dedicated RF receiver coil and an IWF sequence. A phantom, a cadaver finger specimen and the fingers of two normal controls and six arthritic subjects were imaged with a resolution of 156×156×600 microns. The appearance of anatomic structures on the IWF images were compared with images acquired with a regular sequence. The images were reviewed by two musculoskeletal radiologists for the depiction of anatomical structures and for the presence of abnormalities.

Results—The high-resolution images revealed detailed structures of the finger joints not detectable using typical clinical resolution. The IWF sequence gave more realistic depiction of subchondral bone thickness, and avoided false bone erosions displayed in the regular sequence. It also allowed better visualization of ligaments and tendons.

Conclusion—This pilot study shows the feasibility and the potential usefulness of high-resolution IWF imaging for finger joint evaluation. This technique may be useful for the diagnosis and treatment assessment of arthritis, and for the study of joint disease pathogenesis.

Keywords

High-resolution MRI; water-fat imaging; chemical-shift artifacts; musculoskeletal MRI; finger joints; arthritis

INTRODUCTION

Finger joints are among the first structures affected by rheumatoid (RA) and psoriatic (PsA) (1), and they are also commonly involved in osteoarthritis (OA) (2). In RA and PsA, early diagnosis is critical since bone erosions, which are thought to be irreversible, often appear during the initial months of joint inflammation (3–5).

MRI is an imaging modality of choice for the diagnostic evaluation of arthritis in small joints. It detects erosive changes of arthritic diseases with greater sensitivity than plain films, and allows direct visualization and assessment of synovitis and bone marrow lesions (7). Unfortunately, its use in the evaluation of fingers has been hindered by inadequate image resolution and chemical-shift artifacts (8).

Insufficient resolution leads to partial volume averaging that limits the detection of small erosions and bone marrow lesions (4, 8–9). To improve resolution for finger imaging, we developed a dedicated finger RF coil similar in design to the one reported in reference (10).

Chemical-shift artifacts arise from the difference in resonance frequencies of water and fat, causing a spatial misalignment between the two chemical species on MR images. Chemical-shift artifacts alter the appearance of bone and soft tissue structures at the fat/structure interfaces (11). For instance, bone marrow fat may be shifted into areas of signal void in the subchondral bone, producing an apparent change in fat/bone interfaces (12). Besides, chemical-shift artifacts may resemble erosive changes (8). Studies found 13% – 19% mismatch between MR erosion and lesions detected with CT, and concluded that CT is more reliable since not all erosions seen on MR truly represent bone destruction (13, 14). Though fat suppression can eliminate chemical-shift artifacts, non-fat-suppressed images are required to evaluate changes in subchondral bone plate and trabecular bone. While sequences based on Dixon technique (15), such as IDEAL (16), have become available on clinical MRI systems and can provide images free of chemical-shift artifacts, these sequences require the acquisitions of three data sets that increase scan time. To address the need for a fast MRI technique without chemical-shift artifacts, an interleaved water/fat (IWF) pulse sequence was developed (17). It incorporated spectral-spatial excitation to obtain water images and fat images separately in a single acquisition time, and produced water+fat images free of chemical-shift artifacts. In this study, we examined the use of the IWF sequence with our dedicated finger RF coil for high-resolution IWF imaging in both control and arthritic finger joints.

MATERIALS AND METHODS

The study was conducted on a 1.5T MRI scanner (GE Healthcare, Milwaukee, WI) equipped with TwinSpeed gradients with a maximum amplitude of 40mT/m and maximum slew rate of 150mT/m/ms.

A custom-built RF receive coil consisted of a cylindrical loop 2.9cm in diameter and 2.0cm in width made of copper tape (Figure 1a). Its design was similar to the coil reported in reference (10). A phantom consisted of sodium chloride solution (at 0.38% to simulate the coil loading of a finger) was imaged using this coil and a GE 3-inch surface coil commonly

used for clinical high resolution imaging. The SNR performance of the two coils were evaluated and compared with each other.

An IWF 3D gradient echo (GRE) sequence (17) modified from the regular 3D GRE sequence was implemented on the MR scanner (Figure 1b). Binomial 1-3-3-1 spectral-spatial selective RF pulses were used for RF excitation. Selective excitation of either water or fat was carried out by transmitting RF pulse at the frequency of the given chemical species. Water and fat were separately excited and acquired in an interleaved manner at every half repetition time (TR) period. Water-only, fat-only and water+fat images were reconstructed from the acquired data on a remote computer.

For the *in vivo* study, eight subjects were included. They consisted of two normal volunteers, five PsA subjects and one OA subject. The subjects were placed in either a prone or supine position with the hand extended superior and at right angle to the head. One finger joint was imaged for each subject, with an arthritic joint selected for the PsA and OA subjects. The finger joints imaged in this study included the distal interphalangeal (DIP) and proximal interphalangeal (PIP) joint of the second and third digits as well as the interphalangeal joint of the thumb. The imaging parameters were field-of-view (FOV) 4 cm, matrix 256x256, in-plane resolution 156x156 microns, slice thickness 600 microns and full-echo acquisition. For the first three subjects, a TR of 60msec and echo time (TE) of 15msec were used and the acquisition time was 8:15mins. For the latter five subjects, the TR and TE were reduced to 52msec and 12msec respectively (which were the minimum values for the given set of imaging parameters used in this study) and the scan time became 7:10mins. This change was made to reduce the scan time, and all the images presented in this paper were obtained with this setting. The flip angle used was 20° to 40°, a range commonly used in musculoskeletal imaging, with the value being 20° for the last five subjects. Besides the IWF scan, both regular GRE fat-suppressed (FS) and non-fat-suppressed (NFS) images were also acquired using the parameters stated above, each with the same scan time as the IWF sequence. A receive bandwidth of ± 15.6 kHz (122 Hz/pixel) was used, corresponding to a chemical shift between water and fat of about 1.8 image pixels. Readout gradient (frequency encoding) direction was chosen to be along the finger to avoid aliasing artifacts in the phase encoding direction. For one normal subject, additional images were acquired using spin echo (SE) sequence with typical clinical parameters of TR 600 msec, TE 13 msec, FOV 10 cm, matrix 256x256, slice thickness 2.5 mm and receive bandwidth of ± 15.6 kHz. After scanning, the finger images were evaluated by two experienced musculoskeletal radiologists separately for the depiction of 1) normal anatomies including subchondral bone thickness, tendons and ligaments, and 2) abnormalities including bone erosion, bone proliferation and cartilage erosion. The imaging protocol was approved by the Research Subject Review Board of our institution, and informed consent was obtained from each subject.

Phantom and *in vitro* studies were also conducted to demonstrate the effect of chemical-shift artifacts and to verify their removal in the IWF sequence. The phantom consisted of a test tube containing water and vegetable oil that produced fat signal. It was imaged using the coil and sequence settings mentioned above. For the *in vitro* study, a cadaver finger specimen from an adult male donor with no record of arthritis was obtained via the National Disease Research Interchange and was imaged. Images were acquired using the IWF and the regular

GRE sequences as well as these two sequences but with the polarity of the readout gradient reversed. By reversing the readout gradient polarity, chemical-shift artifacts appear differently, which can then be recognized by comparing the images with and without gradient reversal.

RESULTS

In the sodium chloride phantom test, the dedicated finger coil was found to improve SNR by a factor of 4.4 over the GE 3-inch surface coil.

In the water/oil phantom test, chemical shift artifact was observed on the images obtained using the regular sequence at the water/oil interface in the readout gradient direction. This artifact was not seen on the IWF images (Fig. 2a, b). On the regular GRE NFS images of the finger specimen, the subchondral bone appeared to be thicker on one side of the joint than the other (Fig. 2c, d). When the polarity of the readout gradient was reversed, the thicker side became the thinner side and vice versa. In contrast, the IWF sequence depicted similar subchondral bone thicknesses on both sides of the joint regardless of the gradient polarity (Fig. 2e, f). Therefore, the phantom and the specimen studies demonstrated the presence of chemical-shift artifacts in the regular sequence and their removal in the IWF sequence.

In the *in vivo* study, the high-resolution IWF imaging technique was able to reveal anatomical details of the articular cartilage, subchondral bone, trabecular structures, joint capsule, ligaments, musculotendinous structures and entheses (Fig. 3). These details were not observed on the SE images obtained using typical clinical resolution. As in the specimen study, the high-resolution IWF sequence depicted similar subchondral bone thickness on both sides of the joint while both the SE and the high-resolution regular GRE NFS sequences showed different bone thickness. The IWF water-only images also provided good fat suppression in the suppression of bone marrow (Fig. 3).

The high-resolution IWF technique was used successfully on all subjects with different stages of arthritic diseases. In a PsA subject, the regular GRE NFS images showed a cortical break in the finger joint, but the IWF water+fat images revealed that the bone was intact (Fig. 4). Besides providing more accurate depiction of bone structures, the removal of chemical shift artifacts also facilitated the visualization of ligaments and tendons, which were more clearly observed on the IWF images than images obtained using the regular sequence (Fig. 5).

DISCUSSION

In this study, we have demonstrated the feasibility and advantages of the IWF sequence for high-resolution MRI of finger joints. The results showed that the elimination of chemical-shift artifacts provided a more realistic depiction of bone structures, which could prevent misdiagnosis of bone erosion in the finger joints. This is particularly relevant to the evaluation of arthritis that often involves bone resorption and cartilage degradation. Indeed, bone erosion and subchondral bone thickness are critical outcome measures for understanding both clinical and pathologic factors that lead to joint inflammation and damage.

Though higher receive bandwidth may be used in conventional GRE NFS sequences to reduce chemical-shift artifacts, it is problematic in high-resolution imaging. First, increased receive bandwidth causes a proportional increase in readout gradient amplitude, and reduces the highest image resolution achievable under a given maximum gradient limit. Second, it reduces SNR that is inversely proportional to the receive bandwidth. With the IWF sequence, lower receive bandwidth can be used to improve SNR and spatial resolution. In this study, a bandwidth of ± 15.6 kHz was used, which was the default bandwidth of the GRE sequence on our GE 1.5T scanner. The image resolution obtained in this study was the highest reported for MR imaging of arthritic fingers at 1.5T to date. Compared with a recent study (2), our acquired (not displayed) resolution, in terms of the inverse of voxel volume, was twice as high.

Another advantage of the IWF sequence is that it obtains both water-only and water+fat images in one single scan, and saves imaging time over the conventional separate FS and NFS scans. In this study, the total imaging time of the regular GRE sequence was twice as long as the IWF sequence since each of the FS and NFS scans used the same TR and acquisition time as the IWF sequence. Though shorter TR and TE values could have been used in the regular GRE sequence to reduce scan time, the combined scan time for FS and NFS would still be longer than the IWF single acquisition. For the given set of imaging parameters used in this study, the minimum TR and TE values for the FS scan are 37msec and 9msec, while those for the NFS scan are 21msec and 9msec respectively, resulting in a combined imaging time of 8:03mins for the GRE FS and NFS scans compared to that of 7:10mins for the IWF scan. Thus, the IWF sequence provides both FS (water-only) and NFS (water+fat) images in a shorter scan time, while removing chemical shift artifacts in the GRE NFS images.

Although Dixon-based water-fat sequences such as IDEAL are also free of chemical-shift artifacts, they require multiple data acquisitions and longer imaging time (16). Recently, new investigative water-fat sequences based on Dixon technique were developed for faster acquisition (18, 19). However, they may not be applicable for high-resolution finger imaging. A single-point Dixon technique (18) may fail in areas where water and fat are separated by some distance. Since bone, tendon and ligament structures in musculoskeletal systems can give rise to a water-fat separation condition, this technique may not be suitable for musculoskeletal imaging. On the other hand, a multi-echo sequence (19) uses relatively high receive bandwidth in order to achieve small echo spacing and to allow for short TE values. The bandwidths of at least ± 41.67 kHz (320 Hz/pixel) stated in the paper (19) are higher than values commonly used at 1.5T. These higher bandwidths limit image resolution, and may prohibit the resolution used in this study from being obtained.

A limitation of the IWF sequence is that the spectral-spatial binomial excitation used in the sequence leads to an increase in the minimum slice thickness. On our MRI system with maximum gradient amplitude of 40mT/m, the minimum slice thickness for 2D imaging is 2.9 mm, which is too thick for finger imaging. Consequently, the IWF sequence was used only for 3D acquisition. Nevertheless, this may not present a major drawback since 3D acquisition is generally more SNR efficient than 2D imaging (20) and is therefore the preferred approach for high-resolution finger MRI.

Another limitation of this study is that imaging was conducted only on single joints due to the dedicated RF coil used. However, there are some clinical applications in which it is sufficient to image only one finger joint, such as 1) the differentiation of erosive OA from PsA, which is a common clinical problem and is an important one as anti-TNF treatment is effective for PsA but not OA, and 2) the evaluation of bone erosion and new bone formation in arthritis. On the other hand, the IWF technique can be used with larger FOV and standard 3-inch surface (or other commercially available) RF coils for comparative assessment of the fingers and wrist joints. Moreover, we plan to develop a phased array coil that covers a larger field-of-view while providing high SNR to support high-resolution imaging of multiple joints. This will provide a more comprehensive view of joint inflammation and destruction in multiple joints that should be more helpful to clinicians.

In this pilot study, we have shown that the IWF sequence is able to 1) eliminate chemical-shift artifacts, 2) reduce scan time compared to regular GRE FS and NFS acquisitions and 3) support high-resolution acquisition for finger joint imaging. We have also demonstrated the potential of high-resolution IWF imaging for improving the depiction and evaluation of finger joints. The findings of this study may also apply to other water-fat MRI techniques free of chemical-shift artifacts and support high-resolution finger imaging. In the future, we plan to conduct studies at 3T where 1) SNR is higher to support even higher image resolution and 2) chemical shift artifacts are generally more severe and their removal is even more important. High-resolution IWF imaging may be useful for the diagnosis and treatment assessment of arthritis, and may also facilitate pathogenesis studies of joint diseases.

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Figure 1.

A photo of the dedicated finger coil with a subject's finger inserted (a) and pulse sequence diagram of the IWF sequence (b).

Figure 2.

Phantom images demonstrated that chemical shift artifact (dark arrow) in the regular non-fat-suppressed sequence (a) was removed in the IWF sequence (b). Regular coronal images (c) of a PIP joint of the cadaver finger specimens showed that the subchondral bone was thicker on the proximal (P) side than the distal (D) side. Upon reversal of the readout gradient polarity, the subchondral bone appeared thicker on the distal side instead (d). For the IWF images (e), the subchondral bone thickness was similar on both sides of the joint, which did not change with gradient reversal (f).

Figure 3.

High-resolution sagittal IWF water+fat images (a) obtained from a PIP joint of a normal subject depicted anatomical details of the finger joint. The subchondral bone thickness appeared similar on both sides of the joint in the IWF images (a) but not on the regular non-fat-suppressed images (b). The IWF water-only image (c) showed good fat suppression in the bone marrow. The SE images obtained using typical clinical resolution (d) were not able to depict anatomic details as in the high-resolution images, and they were affected by chemical-shift artifacts as seen in the subchondral bone.

Figure 4.

In the sagittal images of a DIP joint of a PsA subject, the non-fat-suppressed image (a) showed a false cortical fissure (circle) that was not present on the IWF water+fat image (b). Similar findings were observed in the reformatted coronal images of the non-fat-suppressed (c) and IWF water+fat (d) images. The fat-suppressed image (e) and the water-only IWF image (f) suppressed the bone marrow signal near the false cortical fissure, further confirming that the cortical bone surrounding the bone marrow at that location was intact.

Figure 5.

In the thumb of the OA subject, joint space narrowing was observed in both the coronal IWF water+fat image (a) and the regular non-fat-suppressed image (b). However, the regular image (b) showed different subchondral bone thickness compared to the IWF image (a). Besides, the collateral ligaments (arrows) were better visualized in the IWF image (a) as they were obscured by the presence of nearby chemical-shift artifacts in the regular image (b).