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Reproducibility of the quantitative assessment of cartilage morphology and trabecular bone structure with magnetic resonance imaging at 7 T

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Abstract

To assess the reproducibility of quantitative measurements of cartilage morphology and trabecular bone structure of the knee at 7 T, high-resolution sagittal spoiled gradient-echo images and high-resolution axial fully refocused steady-state free-precession (SSFP) images from six healthy volunteers were acquired with a 7-T scanner. The subjects were repositioned between repeated scans to test the reproducibility of the measurements. The reproducibility of each measurement was evaluated using the coefficient(s) of variation (CV). The computed CV were 1.13% and 1.55% for cartilage thickness and cartilage volume, respectively, and were 2.86%, 1.07%, 2.27% and 3.30% for apparent bone volume over total volume fraction (app.BV/TV), apparent trabecular number (app.Tb.N), apparent trabecular separation (app.Tb.Sp) and apparent trabecular thickness (app.Tb.Th), respectively. The results demonstrate that quantitative assessment of cartilage morphology and trabecular bone structure is reproducible at 7 T and motivates future musculoskeletal applications seeking the high-field strength's superior signal-to-noise ratio.

Keywords: Magnetic resonance imaging; 7 T; Cartilage morphology; Trabecular bone structure; Reproducibility

1. Introduction

The high signal-to-noise ratio (SNR) of ultra-high-field magnetic resonance imaging (MRI) has great potential for improving soft-tissue contrast in musculoskeletal imaging. Some preliminary studies have examined SNR, contrast-to-noise ratio (CNR) and relaxation times in knee joints at ultra-high fields [1–3]. However, to our knowledge, no studies of quantitative musculoskeletal imaging have been published. A previous study has demonstrated that sharper delineation between femoral and tibial cartilages was observed at 7 T compared to 3 T [3]. Global increases of 45% in SNR and of 55% in CNR for cartilage assessment, and of 60% in SNR for trabecular bone were reported in the study after comparing the images acquired at 7 T with those acquired at 3 T. Despite the superior SNR, ultra-high-field MRI faces several challenges, such as increased chemical shift differences, radiofrequency (RF) power deposition, and main (B_0) and RF (B_1) field inhomogeneities.

The purpose of this study is to examine the reproducibility of quantitative measurements of knee cartilage morphology and trabecular bone structure at ultra-high fields. Quantitative musculoskeletal imaging has been employed at standard field strengths to assist in the clinical diagnosis of diseases such as osteoarthritis (OA) and osteoporosis (OP), to monitor the progression of diseases and to evaluate response to treatment with structure/disease-modifying drugs [4–7]. The measurement of cartilage morphology may provide a biomarker for evaluating the long-term progression of OA. The measurement of trabecular bone structure with MRI offers a quantitative assessment of OP progression and therapeutic monitoring in patient studies [8]. In addition, the superior SNR of ultra-high-field strengths is expected to improve image quality and to assist in evaluating cross-correlations

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Table 1
Comparison of the sequence parameters employed at 3 and 7 T for cartilage and trabecular bone measurements and their corresponding SNR and CNR

Sequence name	FOV (cm)	Matrix/ NEX	T_R/T_E (ms)	Number of sections	Slice thickness	Imaging time	Flip angle (°)	Bandwidth (kHz)	SNR	CNR
SPGR 3 T	14	512×512/1	15.1/3.5	94	1	12 min 6 s	12	31	1	1
SPGR 7 T	14	512×512/1	17/3.72	94	1	13 min 36 s	10	62	1.52	1.63
Fiesta-c 3 T	10	512×384/2	11.1/3.7	50	1	10 min 40 s	60	31	1	
Fiesta-c 7 T	10	512×384/2	11.3/2.45	50	1	10 min 40 s	40	41	1.59	

NEX, number of excitations.
The SNR and CNR at 3 T were normalized to 1.

between cartilage and bone changes during the progression of OA [9,10].

2. Methods

Imaging was performed on a 7-T GE Excite MR scanner (General Electric Healthcare, Milwaukee, WI) with a two-channel transmit/receive quadrature coil (Nova Medical, Inc., Wilmington, MA). All subjects gave informed consent, in accordance with Institutional Review Board guidelines at our medical center.

2.1. B0 field mapping

A series of two-dimensional (2D) gradient-recalled echo (GRE) scans of one subject was acquired to evaluate the homogeneity of the B_0 field. The subject received two axial scans and two sagittal scans, with echo times differing by 1 ms. All GRE scans were acquired with the following: field of view (FOV)=16 cm, slice thickness=5.6 mm, acquisition matrix=256×256, time of echo T_E=5 or 6 ms, time of repetition T_R=30 ms.

2.2. Data acquisition

Six (four male and two female) healthy volunteers (age range, 30–49 years) were recruited for the quantification study. Additionally, one subject was scanned at both 3 T (GE Signa MR scanner) and 7 T to evaluate the effect of field strength on SNR and CNR. A quadrature receiver coil (Pfizer, Inc., New York, NY) was used for the 3-T scan.

A sagittal three-dimensional (3D) fat-suppressed high-resolution spoiled gradient-echo (SPGR) image was acquired to analyze cartilage morphology, and a 3D fully refocused steady-state free-precession (SSFP; GE Healthcare Fiesta-c sequence) image was acquired to quantify the trabecular bone structure parameters. Sequence parameters are shown in Table 1. To compensate for the increased chemical shift that is presented at ultra-high fields, data sampling bandwidth was increased from 31 kHz (which is routinely used in lower-field clinical scan protocols) to 62 kHz for the SPGR sequence, and from 31 to 41 kHz for the Fiesta-c sequence. The flip angle of Fiesta-c was also reduced from 60° (as regularly used in lower-field clinical scan protocols) to 40° at 7 T. This was performed to accommodate the changes in T_1 and T_2 at high-field strengths for optimized SNR. T_R was chosen to be 17 ms for the SPGR sequence due to the consideration of specific absorption rate constraints, adequate SNR and minimal imaging time. Optimization of the flip angle to achieve a high SNR in the cartilage with the SPGR sequence is shown in Fig. 1. The maximum SNR was achieved at a 10° flip angle. Sagittal SPGR images were acquired to cover the whole tibiofemoral joint. Axial Fiesta-c images were acquired to cover the distal femur. All subjects were repositioned, and all scans were repeated to examine the measurements' reproducibility.

2.3. Data processing

Data postprocessing was performed on a Sun workstation (Sun Microsystems, Palo Alto, CA).

The B_0 field was mapped by calculating the phase difference between the two GRE scans and dividing the 1-ms phase evolution time. The resulting images were unwrapped using PRELUDE [11].

An in-house program [12] programmed in MATLAB (Version 7; The MathWorks, Inc., Natick, MA) was employed for cartilage segmentation, as well as for the computation of cartilage thickness and volume. Five different compartments were defined for cartilage segmentation: lateral femoral condyle/medial femoral condyle (LFC/MFC), lateral tibia/medial tibia (LT/MT) and patella (P). The mean cartilage thickness and the total cartilage volume over all segmented cartilages were also calculated.

Analysis of trabecular bone structure parameters was performed using an in-house-developed image analysis software [13] programmed in IDL (RSI, Boulder, CO) and

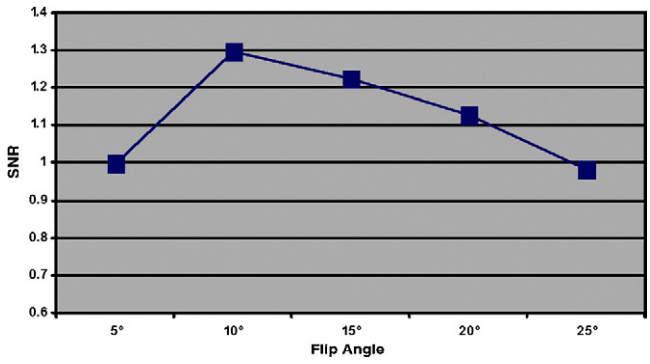

Fig. 1. 3D SPGR sequence optimization. Experimental results indicated that a flip angle of 10°, compared with other flip angles, provided maximum SNR. All SNRs shown here were normalized to the SNR achieved at a flip angle of 5°.