

Investigation of Regional Influence of Magic-Angle Effect on T₂ in Human Articular Cartilage with Osteoarthritis at 3 T

Ligong Wang, PhD, Ravinder R. Regatte, PhD

Rationale and Objectives: The objectives of this research study were to determine the magic-angle effect on different subregions of in vivo human femoral cartilage through the quantitative assessment of the effect of static magnetic field orientation (B_0) on transverse (T₂) relaxation time at 3.0 T.

Materials and Methods: Healthy volunteers ($n = 5$; mean age, 36.4 years) and clinical patients ($n = 5$; mean age, 64 years) with early osteoarthritis (OA) were scanned at 3.0-T magnetic resonance using an 8-channel phased-array knee coil (transmit-receive).

Results: The T₂ maps revealed significantly greater values in anterior than in posterior regions. When the cartilage regions were oriented at 55° to B_0 (magic angle), the longest T₂ values were detected in comparison with the neighboring regions oriented 90° and 180° (0°) to B_0 . The subregions oriented 180° (0°) to B_0 showed the lowest T₂ values.

Conclusions: The differences in T₂ values of different subregions suggest that magic-angle effect needs to be considered when interpreting cartilage abnormalities in OA patients.

Key Words: Osteoarthritis; T₂ mapping; cartilage imaging; magic-angle effect; transverse relaxation time.

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The primary macromolecules in human cartilage are collagen type II and proteoglycans. Proteoglycan is responsible for much of the compressive stiffness through electrostatic repulsion, whereas collagen provides the tensile and shear strength (1). The earliest biochemical changes in osteoarthritis (OA) are the modifications at the molecular level of cartilage matrix, which occur without obvious morphologic changes. The loss of glycosaminoglycan and the collagen breakdown are the typical characteristics of early OA (2–4).

Human articular cartilage is a highly ordered and depth-dependent ultrastructure and is essentially defined by the organization of the collagen fibrils (5). Collagen fibers in his-

tology have three predominant organizational zones across the depth of the cartilage tissue. In the superficial (tangential) zone, the collagen fibrils are parallel to the cartilage surface, whereas in the radial (deep) zone, the fibrils are oriented perpendicular to the surface. However, in the transitional (middle/intermediate) zone, the arrangement of collagen fibers is almost random. The characteristic arrangement of collagen fibers results in the “magic-angle effect” and exhibits anisotropic properties when measured at different tissue depths and from different physical orientations in the proton magnetic resonance (MR) images (5–7).

T₂ mapping is a promising approach for assessing the underlying collagen microstructure in the extracellular matrix of articular cartilage. Damages to the extracellular matrix of articular cartilage and the increase of water content in degenerated cartilage give rise to increases in the T₂ relaxation times (8–10).

Previous studies (5–7,11–14) have revealed that the T₂ values will be elevated when the articular cartilage surface is placed at approximately 55° with respect to the external static magnetic field B_0 . The signal changes that occur at angles approximating 54.7° are known as the magic-angle phenomenon because the dipolar interaction between two nuclei scales is $3 \cos^2 \theta - 1$, where θ is the angle between the internuclear vectors joining the nuclei and B_0 . The dipolar interaction that tends to reduce signal

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From the Collaborative Innovation Center of Radiation Medicine of Jiangsu Higher Education Institutions, Jiangsu Provincial Key Laboratory of Radiation Medicine and Protection, School of Radiation Medicine and Protection, Medical College of Soochow University; School for Radiological and Interdisciplinary Sciences (RAD-X), Soochow University. Office of Ligong Wang, 2nd Floor, Bldg. 402, 199 Ren Ai Rd, Suzhou Industrial Park, Suzhou, Jiangsu 215123, China (L.W.) and Quantitative Multinuclear Musculoskeletal Imaging Group (QMMIG), Center for Biomedical Imaging, Department of Radiology, New York University Langone Medical Center, New York, NY 10016, USA (R.R.R.). Received February 16, 2014; accepted July 25, 2014. Address correspondence to: L.W. e-mail: ligong.wang@hotmail.com

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intensity will vanish when $(3 \cos^2 \theta - 1) = 0$, which is satisfied when θ equals 54.7° .

One manifestation of this magic-angle phenomenon is that the T_2 decay of cartilage tissue is greatly retarded, and the signal intensity is maximal when the collagen fiber is oriented at this angle in relation to B_0 (5,11). Other investigators (7,10,13,15–19) reported that T_2 relaxation reflects the ability of free water proton molecules to move and to exchange energy inside the cartilaginous matrix. The T_2 variation may be due to the regional differences in cartilage compression. The weight-bearing portion of the femoral-tibial joint is subject to compressive force that may lower the water content of the cartilage.

The aim of this work was to perform a quantitative assessment of the effect of B_0 orientation on T_2 relaxation times to determine the magic-angle effect on different subregions of in vivo human femoral cartilage at 3.0 T. We measured and compared the global and regional changes of femoral cartilages in T_2 relaxation times for healthy controls and OA patients using quantitative T_2 relaxation method at 3.0 T.

MATERIALS AND METHODS

Human Subjects

Five healthy volunteers ($n = 4$ men and $n = 1$ woman, ranging in age from 24 to 45 years, with an average age of 35.6 years) and five patients ($n = 3$ men and $n = 2$ women, ranging in age from 53 to 82 years, with an average age of 65 years) with clinically documented early knee OA by radiography (Kellgren–Lawrence [K–L] grading scale 1 and 2) (20) were recruited. All healthy volunteers and OA patients were scanned for T_2 mapping. To limit the patient motion between acquisitions, the knee was fixed with foam padding, which is very important because the subject's positioning is extremely critical for subsequent orientation studies of regional cartilage T_2 values. All the human subjects provided informed consent to participate in the research, which was approved by our institutional review board.

Imaging Hardware

All MRI experiments were performed on a 3.0-T clinical MR scanner (MAGNETOM Tim Trio; Siemens Medical Solutions, Erlangen, Germany). An 18-cm diameter, 8-channel, transmit–receive, phased-array (PA) knee coil was used for all the imaging measurements.

Imaging Protocol

The protocol included the following sequence: 2D sagittal T_2 -weighted spin-echo (SE) imaging with the following imaging parameters: time of repetition (TR)/time of echo (TE) = 4000/16.5, 33, 49.5, 66, 82.5 milliseconds; field of view = 15 cm; matrix = 256×256 ; bandwidth = 130 Hz; slice thickness = 1.5 mm.

MR Images Analysis and Processing

All the MR images were analyzed based on global and regional compartments. Three subregions (55° , 90° , and 180° [0°] with respect to B_0) were defined in the femoral cartilages of each subject. The in-house developed routines in MATLAB (version 7.1; The MathWorks, Natick, MA) and C++ were used for offline processing of the acquired MR images.

T_2 -weighted images with the shortest TE (16.5 milliseconds) were used for the segmentation of femoral cartilages. Regions of interest (ROIs) were segmented manually for each slice for all the subjects. These segmentations were used to draw ROIs for each MR image with different TE values. T_2 maps were computed with custom-built MATLAB routines using the corresponding expression (10,12,13,15).

The intersubject variability of the T_2 maps was quantified using root mean square coefficients of variation percentage (RMS-CV%), and the Student t test was used to determine whether there were any statistically significant differences in the T_2 values among the local/global regions of femoral cartilages for asymptomatic and OA subjects.

RESULTS

Figure 1a displays the three subregions oriented 55° , 90° , and 180° (0°) related to the external static magnetic field B^0 in the anterior and posterior regions with the corresponding magnified details showing the highly organized collagen structure of the human cartilage, respectively. Figure 1b is the plot showing the $(3 \cos^2 \theta - 1)$ factor as a function of angle with respect to B_0 for nuclear dipolar interaction. In the two positions with two arrows identifying the discrete sampling points where $(3 \cos^2 \theta - 1) = 0$, the θ equals approximately 55° and 125° , respectively, and the magic-angle effect may emerge in these two sampling positions. Other arrows show the sampling points where the $(3 \cos^2 \theta - 1)$ factor has the maximal and minimal values, respectively.

Two representative T_2 (top row) slices obtained from an OA patient overlaid onto the shortest TE (16.5 milliseconds) were displayed in Figure 2a and b, respectively. Figure 2c and d correspondingly showed a series of subregions on the femoral cartilage segmented at every 20° with respect to B_0 . Figure 2e is the T_2 profiles of the corresponding subregions segmented in Figure 2c or d. As shown in Figure 2e, the T_2 values of OA generally were greater than those of healthy controls. In the sections oriented 55° relative to B_0 (magic angle, 120° – 140° and 240° – 260° as shown in Fig 2c or d), the longest T_2 values were detected in comparison with the neighboring sections oriented 90° (100° and 280° as shown in Fig 2c or d) and 180° with respect to B_0 . The subregions oriented 180° relative to B_0 showed the lowest T_2 values. Furthermore, the T_2 values displayed obviously greater values in the anterior than in the posterior regions.

Figure 3 displayed the bar charts of the average anterior and posterior T_2 values in the subregions oriented 55° , 90° , and

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