In-vivo assessment of collagen fiber arrangement in articular cartilage with 7T MRI

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Introduction

In vitro studies of native cartilage samples have shown that high resolution MRI can yield information on the collagen ultrastructure in cartilage [1, 2]. The relaxation properties of hydrogen nuclei in an external field B_0 depend on the orientation of the cartilage sample and may be assessed on T2-weighted (T2w) images. Over the last years, an analytical model has been worked out that quantitatively describes the intensity dependence on the ultrastructure of the collagen network [2, 3]. In this model, the average arrangement of collagen fibers within a voxel is simply characterized by a mean fiber orientation θ (relative to B_0) and an opening angle α (Fig. 1). The purpose of this study was to evaluate whether T2w MRI of the human knee at 7T provides a way to non-invasively assess the collagen network structure and the boundaries within the cartilage layers in particular.

Methods and Materials

The right knees of three healthy volunteers (male, 25-30 y.o.) were examined in a 7T whole-body MR scanner (MAGNETOM 7T, Siemens Healthcare, Erlangen, Germany) with an 8 channel phased array coil (RAPID Biomedical, Rimpar, Germany). Sagittal images of the lateral condyles were acquired with a T2w multi-echo SE-sequence (TR/TE=3030/12–96 ms; 8 echoes; FOV=130 × 130 mm; slice thickness=1 mm; matrix size=448 × 448; acquisition time ≈23 min). Small ROIs were defined in the femoral and tibial condyles near the joint contact area with a width of three pixels and a height according to the individual thickness of the cartilage (Fig.2). T2-maps were calculated from the echo-time dependence of the signal intensities. Intensity profiles as a function of cartilage depth were calculated for each echo time by averaging the signal intensities over the width of the ROI. Further analysis was performed on the image of that echo time where the intensity profile best matched that of the T2 map. All intensity profiles were then normalized assuming the minimum and maximum values to correspond to the theoretical values at α =0° (radial) and α =90° (isotropic). The correspondence of normalized intensity value and opening angle α within the fascicle model (Fig. 1) was then used to convert the intensity profiles to depth-dependent profiles of α. The boundary between radial and transitional zone (R/T boundary) was assumed at α =35° (Fig. 3).

Table 1. Summary of cartilage measurements

	Volunteer 1		Volunteer 2		Volunteer 3	
	Femur	Tibia	Femur	Tibia	Femur	Tibia
Thickness [mm]	3.8	4.6	3.2	5.2	2.9	4.1
θ [°]	15	18	25	10	14	5
TE* [ms]	60	60	72	60	60	60
R/T boundary	0.52	0.75	0.52	0.92	0.37	0.75

* TE of the analyzed image

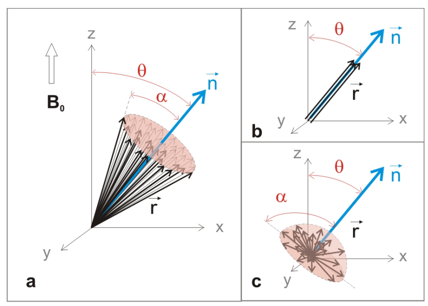

Fig. 1. Fascicle model of the collagen fiber arrangement in cartilage. **a:** general case; **b:** special case α=0° corresponds to radial arrangement of fibrous network (deep/radial zone); **c:** special case α=90° corresponds to isotropic structure (transitional zone).

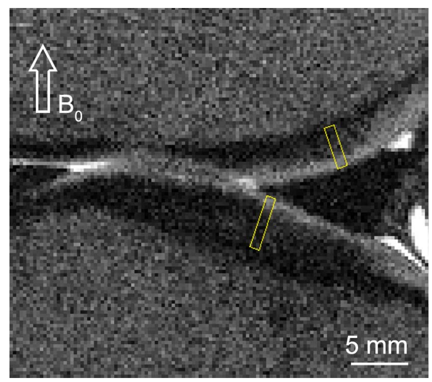

Fig. 2. Sagittal MR image of femoro-tibial joint (lateral condyles) at TE=60 ms (30 y.o. male) with ROIs used for analysis.

Results

At 7T, high resolution images of the knee cartilage (voxel size of 0.29 × 0.29 × 1.0 mm^3) had a sufficient SNR for subsequent quantitative analysis (Tab. 1). In 5/6 cases, images at TE=60 ms were used. The relative position of the R/T boundary of the femoral cartilage (0.37–0.52) lay deeper as that of the tibial cartilage (0.75–0.92). In all volunteers, the opening angle α of the femoral cartilage showed a steeper increase near the R/T boundary than that of the tibial one (Fig. 3).

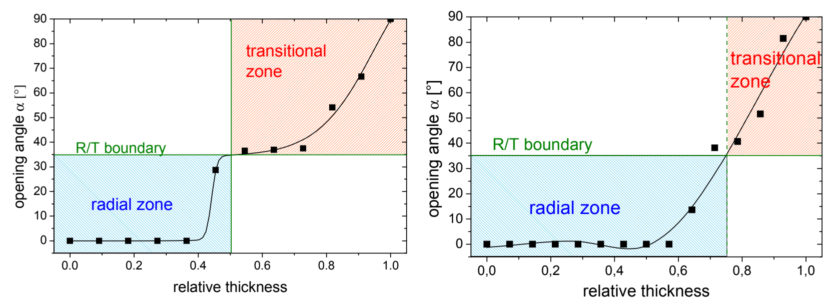

Fig. 3. The α- thickness profiles of articular cartilage (30 y.o. male). **Left:** femur. **Right:** tibia.

Discussion and Conclusions

High-resolution T2w MRI at 7T seems to be a helpful modality to assess the cartilage ultrastructure in vivo. Within the fascicle model, quantitative parameters on the collagen fiber arrangement could be derived from a single MR image. The depth-dependent profiles of the opening angle α were used to define the R/T boundary and thus to estimate the thickness of the radial zone in adult cartilage (Fig. 4). The larger radial zone observed in tibial cartilage is compliant with its fundamental role for the biomechanics of the knee joint. With aging, the radial structures of the cartilage are expected to become more isotropic (Fig. 5). The presented method could therefore be used to non-invasively determine the "biologic age" of cartilage.

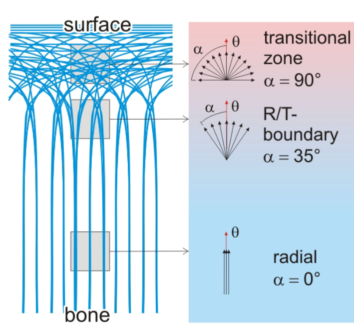

Fig. 4. Schematic illustration of collagen fiber arrangement in adult cartilage with respect to the fascicle model.

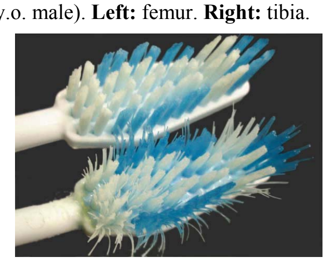

Fig. 5. Illustrating the effect of aging on fiber arrangement. The arrangement of the frayed bristles is more isotropic than that of the newer ones.

References

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