Deformation of cartilaginous collagen fiber network under pressure: a load-bearing MRI study.

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Introduction

The complex organization of collageneous fiber network in joint cartilage and its load conditioned behaviour determines the biomechanical properties of this tissue. It has been shown that the state of health of the cartilage has an influence on the deformation mechanisms of the collagen network under compressive load [1, 2]. Thus, the compression tests could be a successful tool to detect slight arthrotic changes in the cartilage. Many authors assessed the deformation of collagen fiber network under pressure by means of different microscopic techniques. Kääb et al. reported the crimping form of statically compressed fibres (Fig.1a) [3], whereas Thambyah and Broom declare 'chevron-like' bending of fibrous structure under loading (Fig.1b) [2]. Nötzli and Clark have also found that the changes of the collagen fibres form include both bending and crimping [1].

MR appearance of the cartilage is changing under loading conditions because the signal intensity is altering by the collagen network deformation. The reason behind this effect is the MR intensity dependence on the orientation of collagen fibrils in the static magnetic field B_0 [4], which has been described trough a mean fiber orientation θ and an opening angle α [5]. In general, the intensity dependence on the angles θ and α can be described with the help of following expression:

$$I(\alpha,\theta)=\exp\left\{-\frac{1}{8(1-\cos\alpha)}\times\left[\cos\alpha\left(12\cos^2\theta-9\cos^4\theta-27\cos^2\theta\sin^2\theta-\frac{135}{8}\sin^4\theta+18\sin^2\theta-8\right)+\right.\right. \quad \text{(eqn. 1)}$$

$$\left.\left.+\cos(3\alpha)\left(4\cos^2\theta-\frac{9}{2}\cos^4\theta-\frac{9}{2}\cos^2\theta\sin^2\theta-2\sin^2\theta+\frac{45}{16}\sin^4\theta\right)+\cos(5\alpha)\left(\frac{27}{10}\cos^2\theta\sin^2\theta-\frac{9}{10}\cos^4\theta-\frac{27}{80}\sin^4\theta\right)\right]\Bigg|_0^{\alpha}\right\}$$

In this wise, the cartilaginous collagen matrix deformation under load bearing conditions can be observed by means of non-invasive techniques, such as MRI. In his work, Gründer presented for the fist time a possibility of load-bearing MRI to achieve information about changing collagen fiber orientation under compressive load [5]. In the present study, similar and advanced techniques were applied to discuss the feasible deformation mechanisms of collageneous ultrastructure from the point of view of the load-bearing MRI.

Methods and Materials

For the in vitro experiments, cartilage-bone plugs about 15 mm in diameter were stamped from the femur condyle of the knee cartilage of an adult sheep (3 y). MR examinations were performed at the room temperature on a 7 T Bruker DRX 300 spectrometer (Bruker, Rheinstetten, Germany) equipped with a micro-imaging unit. Two types of MR measurements were performed: orientation dependent MRI and load-bearing MRI. For the orientation dependent MRI, images were acquired using a fast spin-echo sequence (RARE, TE_{eff} = 20 ms, TR = 1500 ms). The samples were rotated in the plane according to the imaging plane in about 10° increments between 0° and 90° with respect to the static magnetic field B_0. The load-bearing MRI was performed with the load pressure distributed over the whole sample surface by means of quick-hardened acryl resin, as described in [5]. The pressure was gradual increased in steps of 0.1 MPa up to 1.0 MPa. A SE sequence (TE = 30 ms: 8 echoes; TR = 500 ms) was used.

Results

The images achieved at the orientation dependent MRI show a strong influence of the specimen arrangement respective to the static magnetic field B_0. At almost each image one or more hyperintense regions occurred, which were interpreted as containing the collagen fibres arranged under magic angle (55°) to B_0. Based on this technique, the profile of natural main fiber orientation over the whole cartilage sample was mapped.

On the MR images of loaded cartilage, a shift of a high intensity region from the side of sample to the center was observed (Fig. 2). With the help of the known natural main fiber orientation, we could calculate the pressure conditioned alteration of the main fiber orientation under pressure σ = 40°/MPa. To evaluate the deformation behavior of collagen fibres, the intensity variation at the side of sample at a point with the polar coordinate β=30° was measured. At this region, the experimental derived intensity behavior exhibits a significant curve with a rapid rise, a flat maximum and a slight loss (Fig. 3). On the MR images, it expresses in the migration of the high intensity area (Fig. 2).

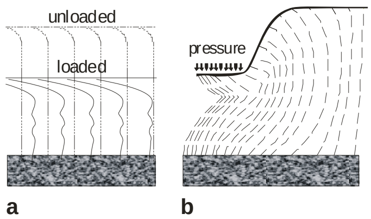

Fig. 1. Deformation of collagen fibres under pressure [2, 3].

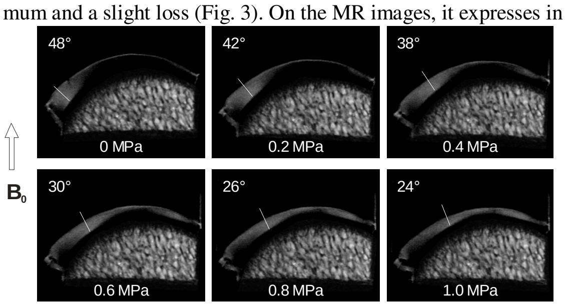

Fig 2. T_2-weighted MRI of loaded cartilage with pressure distributed over the whole sample surface. The polar coordinate β of high intensity region respective to B_0 is indicated.

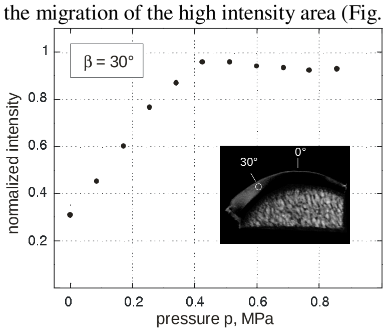

Fig. 3. MR intensity variation at the point of sample with the polar coordinate β = 30°.

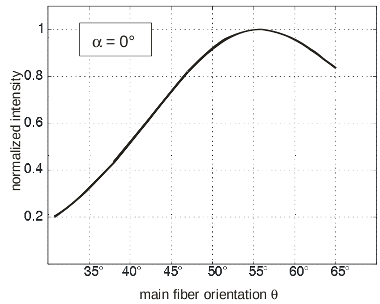

Fig. 4. Theoretical MR intensity at α = 0° and θ changing from 30° to 70° caused by pressure.

Discussion and Conclusions

The presented network deformations (Fig. 1) can be interpreted by means of dipole model describing by eqn. 1. Curved shape of fibres (Fig. 1a) would cause an increase of different local fiber orientations within a voxel, i.e. increase of opening angle α. The bending of collagen columns (Fig. 1b) would shift the mean fiber orientation θ. Theoretical calculated intensity variation for the crimping fibres only (main fiber orientation θ is constant) results in a slight slope of values at the point with β = 30° (θ = 30°), whereas for the bending collagen columns only (open angle α is 0) a bell-shaped curve is derived (Fig. 4). Therefore, primarily the collagen fiber bending in the radial zone of cartilage (Fig. 1b) under pressure could be confirmed. The flat shape of the experimental intensity peak (Fig. 3) could be explained by a simultaneous increase of the opening angle α and the main fiber orientation θ. On Fig. 5, the theoretical curves I(θ) at different opening angles α are shown (grey). Thus, the resulted behavior considered both (slight) crimping and bending of collagen fibres (red) has as a similar shape as the experimental curve.

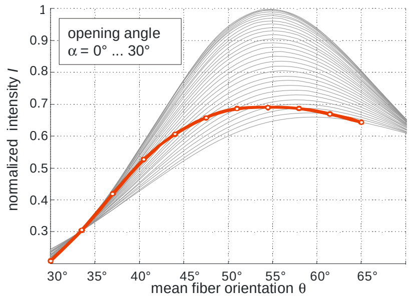

Fig. 5. Theoretical MR intensity behavior at α changing from 0° to 30° simultaneous with θ changing from 30° to 70° (red line).

References

[1] Nötzli H, Clark J. J Orthop Res 1997 15: 76-86; [2] Thambyah A, Broom N. Osteoarthritis Cartilage 2007, 15(12), 1410-1423; [3] Kääb M et al. J Orthop Res 1998, 16: 743-751; [4] Gründer W et al. Magn Reson Med 1998; 39:376-382; [5] Gründer W. NMR Biomed 2006, 19: 855-876.