Validation of chevron-like deformations of collagen fiber network in articular cartilage by means of load-bearing µMRI

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Introduction: The load-dependent collageneous fiber organization in the joint cartilage determines the biomechanical properties of this tissue. It has been shown that the deformation mechanisms of the collagen network under compressive load depend on the morphological and structural intactness of the cartilage [1, 2]. Thus, the analysis of load-reactions of joint cartilage could be a successful tool to detect (slight) arthritic changes. The deformation of collagen fiber network under pressure was detected by means of different microscopic techniques. The compression causes the bending and crimping of collagen fiber [1, 3]. Thambyah and Broom declare a chevron-type shear discontinuity of the fiber orientation in the transitional zone under load in case of an intact tangential surface zone (Fig.1a) [2]. On the other hand, when the tangential layer was disrupted – which was caused by arthritis – the characteristic kink of the chevron model was not observed (Fig.1b). This demonstrates the important functional role of the articular surface for strain-limiting and stress transmission. It was shown that the collagen matrix deformation under load can be observed by means of angle-sensitive T2-weighted MRI [4-5]. With this method, the bending and crimping of the collagen fiber in compressed cartilage could be assumed [6]. In the present study, the feasible deformation mechanisms of collageneous ultrastructure – particularly the fiber bending and crimping – were analyzed by means of load-bearing MRI with the aim to detect the chevron-type shear discontinuity as an imprint of intact tangential layer.

Methods and Materials: For the in vitro experiments, two cartilage-bone plugs (Ø~15 mm) were stamped out from the main weight-bearing region of the left and right medial femur condyles of an adult sheep (3 y.o.). Orientation dependent and load-bearing µMRI with the pressure distributed over the whole sample surface by means of quick-hardened acryl resin [6] was performed on a 7 T spectrometer (Bruker, Germany) equipped with a micro-imaging unit.

Results: Using the dependence of the MR intensity on the sample orientation relative to B_0, the natural regional declination σ_0 of the main fiber orientation from surface normal vector direction was determined. Under compressive load a shift of the high intensity region (magic angle) from the side of sample to the center was observed (Fig.2). From these changes the alteration σ of the main fiber orientation θ of 40°/MPa under pressure was calculated [6]. The decrease $\Delta d/d$ of the cartilage thickness was also determined. For an interpretation of the observed intensity and thickness changes two models of collagen matrix deformation under pressure were assumed:

- model (1): fibers are bending without a kink (Fig. 3a) like in case of a destructed surface layer (Fig. 1b);
- model (2) fibers react with a chevron-type shear discontinuity at a relative depth of 80% (Fig. 3b) which is typical for an intact surface (Fig. 1a).

A simple geometric scheme was used to calculate the relative decrease of the fiber dimension Δl. This apparent reduction of the fiber length can be results from a crimping of the fibers. We assume that a sinus-shaped transformation (Fig. 4) of collagen fibres occurs: $f(x) = a\cdot\sin(\omega x)$ (eqn. 1)

Whereas the curve length L of the fiber should remain constant (due to the incompressibility of collagen), the amplitude a and the frequency ω of the sinus curve alter with the decrease of the apparent fiber length l:

$$L = \int_0^l \sqrt{1 + a^2\omega^2\cos^2(\omega x)}\,\mathrm{d}x \qquad \text{(eqn. 2)}$$

In this way, the unknown settings a and ω of the sinus curve (eqn. 1) describing the fiber transformation can be found. This, in turn, allowed to calculate the maximal angle α_{max} between the mean fiber direction (x axis) and the curve tangent (Fig. 4) defining the maximal fascicle opening angle α of the fiber crimping [5, 6]. The opening angle α together with the fiber bending angle σ determine the MR signal intensity on the T2-weighted images of the cartilage [5]. For the examined cartilage samples the opening angle α at the maximal applied load value of 1 MPa was ~50° for model (1) and ~30° for model (2).

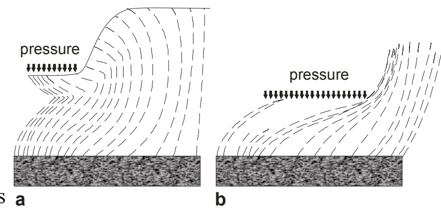


*Fig. 1. Deformation of collagen fibres under pressure with (**a**) an intact and (**b**) a lost of strain-limiting tangential layer [2].*

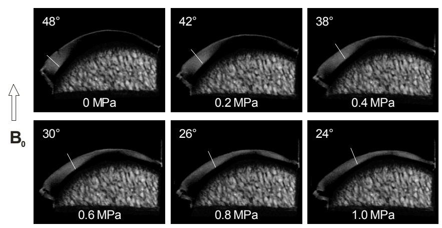


Fig. 2. T_2-weighted MRI of loaded cartilage with pressure distributed over the whole sample surface. The polar coordinate of high intensity region respective to B_0 is indicated.

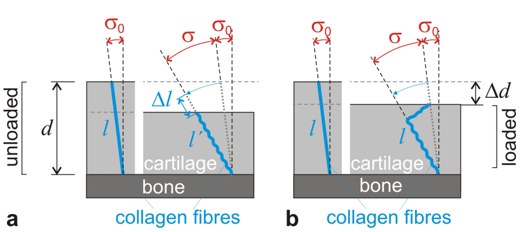
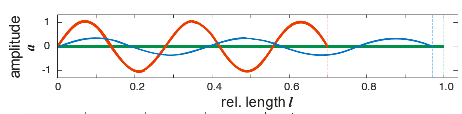


Fig. 3. Simplified schemas for assessment of fiber deformation in case of an intact (a) and a destructed (b) tangential layer. l – unloaded fiber length; l' – loaded (shortened) fiber length; d – thickness.



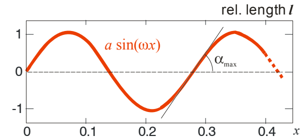


*Fig. 4. **Top:** Assumed sinus-shaped fiber deformation. Green line depicts the uncompressed fiber; blue and red lines exhibit the fiber shape under a slight and a heavy load, respectively. **Bottom:** Assessment of the maximal tangent angle of the sinus-shaped curve which corresponds to the opening angle α.*

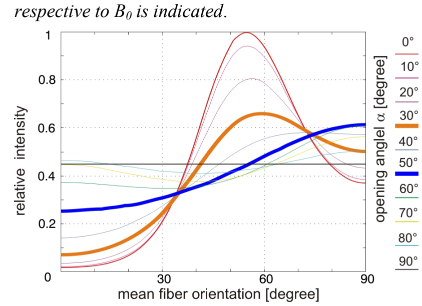


Fig. 5. Theoretical dependence of signal intensity on the orientation relative to B_0 at various opening angles α. Up to the α values of about 30° a specific intensity dependency shape (with a positive and a negative slope) is present.

Discussion and Conclusions: An opening angle α=50° would result in a lost of the orientation dependence of the MR-appearance of the cartilage structure. In case of α=30° it will still remain (Fig. 5). In our experiment, we did observe the orientation dependency of signal intensity up to the maximal applied pressure values. Therefore, the fiber deformation in our experiments can be explained on the basis of model (2) assuming a chevron-type shear discontinuity (Fig. 6).

The present statements of the collagen fiber deformation in compressed cartilage are based on the simplified geometrical assumptions and are supported by scientific observation by means of different microscopic methods. Nevertheless, the derivations of the fiber bending and crimping of the collagen fibres were realized on the basis of angle-sensitive MRI image evaluation only. Although the exact same load experiment conditions used here are not suitable for in-vivo studies, similar techniques could be helpful to develop a method for an early arthritis staging with the help of load-bearing MRI.

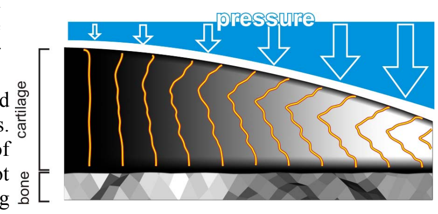


Fig. 6. Illustrating the deformation of collageneous ultrastructure in healthy articular cartilage under load bearing. With increased pressure, the bending and crimping of fibrils occur. The chevron type shear discontinuity reveals an intact tangential layer.

References: [1] Nötzli H, Clark J. J Orthop Res (1997) 15:76; [2] Thambyah A, Broom N. Osteoarthritis Cartilage (2007) 15(12):1410; [3] Kääb M et al. J Orthop Res (1998) 16:743; [4]Gründer W et al. MRM (2000) 43:884; [5] Gründer W. NMR Biomed (2006) 19:855; [6] Garnov N, Gründer W. (2009) Proc. ISMRM, #1979