INTRODUCTION: Articular cartilage resists compressive, tensile and shear forces that are transmitted through the articulating bone ends. During osteoarthritis (OA) the fulfillment of this task is impaired. Quantitative magnetic resonance imaging (MRI) provides means to characterize the structural changes in cartilage during OA [1]. Using MRI, it is also possible to estimate elastic properties of normal cartilage during static and dynamic loading [2,3]. However, the estimation tools for mechanical characteristics of the tissue have been simple, and a more comprehensive insight into time-dependent mechanical behavior has not been achieved.

In the present study, T2 relaxation time mapping and delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) were used to spatially quantify the collagen integrity and proteoglycan (PG) content, respectively [4,5,6]. of normal and spontaneously degenerated bovine articular cartilage. Further, mechanical tests of the same samples were analyzed with an advanced FE model that included a geometrically realistic collagen network [7]. Elastic moduli, related to both collagen network and PGs, were compared to T2; and dGEMRIC, respectively. Thereby, we took the first step towards estimating the mechanical behavior of cartilage by combining MRI and finite element analysis (FEA), and ultimately towards prediction of cartilage biomechanics without an actual mechanical test.

METHODS: Normal (n = 8) and spontaneously degenerated (n = 9) articular cartilage samples without subchondral bone were harvested from lateroproximal bovine patella. Subsequently, the samples were tested by using unconfined compression geometry and stress-relaxation test (10% step, ramp velocity 2 mm/s, 1600 s relaxation time).

For quantitative MRI, the samples were imaged at 9.4 Tesla to determine the T2 relaxation time (spin echo sequence, TR of 2500ms and six TEs between 14 and 84ms). This was followed by a 2.5h equilibration in 1M Gd-DTPA and T2 relaxation time (dGEMRIC) was measured (TE of 14ms, 6 TRs between 100 and 1500ms). The slice thickness was 1mm and the depthwise resolution was 39um. The thickness of each collagenous zone was determined from T2 maps [8].

An axisymmetric FE model of articular cartilage in unconfined compression consisted of four-node poroelastic elements (Fig. 1) [7]. MRI information on collagen network orientation, i.e. thickness of the superficial, middle (bending radius of collagen fibrils) and deep zones, was incorporated into the model for an intact and degenerated sample (Fig. 1) [7,8]. Material parameters of the model, as obtained by fitting FE solution to experimental tests, were Young’s modulus of the solid matrix, $E_s$, initial and strain-dependent Young’s modulus of the fibril network, $E^{0}$ and $E^*$, respectively, and permeability, $k = k_{0} \cdot e^{0}$. Abaqus code was used for the user subroutine was used for the FE calculations and Matlab was used for the optimization of model parameters.

RESULTS: T2 and dGEMRIC relaxation time profiles for normal and degenerated cartilage samples were different (Fig 2, Table 1). Simulations of the fibril-reinforced poroelastic model showed that both the fibril network and PG matrix moduli decreased as a function of cartilage degeneration (Fig 2, Table 1). On the other hand, permeability increased with progressing degeneration (Fig 2, Table 1).

DISCUSSION: T2 and dGEMRIC relaxation time maps can be used to quantify the properties of collagen and content of PGs in articular cartilage, respectively. The spatial MRI parameters show differences between the normal and degenerated articular cartilage [1]. In this study, using the T2 relaxation time profiles of normal and degenerated articular cartilage samples, collagen network orientation was incorporated into the fibril-reinforced poroelastic model. Subsequently, the model-derived values for the moduli of collagen network and PG matrix were compared with the collagen and PG sensitive MRI parameters. The decrease in the values of the collagen network modulus in the model matched with the MRI-detected increase in T2 relaxation time of the superficial layer, known to occur during cartilage degeneration [1]. In the FE model, the reduction of superficial layer thickness decreases effectively the modulus of the superficial collagen network and, consequently, the stress in the superficial zone (Fig. 2). As the modulus of PG matrix decreased and permeability increased, the dGEMRIC index decreased, as detected earlier during cartilage degeneration [1]. This indicates that dGEMRIC can reflect modulus of PGs and fluid flow in the tissue.

This study presents a step towards clinical, non-invasive evaluation of mechanical properties of articular cartilage. While cartilage mechanics is sensitively altered in tissue degeneration, MRI-aided FE-modeling may help the clinical diagnosis of early OA. Furthermore, the monitoring of outcome of surgical cartilage repair techniques, especially from the mechanical point of view, may be improved.

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Table 1: Parameter values of MRI and fibril-reinforced poroelastic model for typical intact and degenerated samples.

<table>
<thead>
<tr>
<th></th>
<th>Intact</th>
<th>Degenerated</th>
</tr>
</thead>
<tbody>
<tr>
<td>dGEMRIC (ms)</td>
<td>399.0</td>
<td>349.3</td>
</tr>
<tr>
<td>T2 (ms)</td>
<td>43.4</td>
<td>85.3</td>
</tr>
<tr>
<td>$E_s$ (MPa)</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>$E^0$ (MPa)</td>
<td>4.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$E^*$ (MPa)</td>
<td>450.0</td>
<td>2.0</td>
</tr>
<tr>
<td>$k \cdot 10^{-5}$ (m²/Ns)*</td>
<td>0.6</td>
<td>3.9</td>
</tr>
</tbody>
</table>

*for the clarification, $k$ is stated at 10% strain from equation $k = k_{0} \cdot e^{0}$.

COMBINATION OF QUANTITATIVE MRI AND DEPTH-DEPENDENT FINITE ELEMENT MODEL FOR THE PREDICTION OF ARTICULAR CARTILAGE FUNCTION

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