

Effects of Shear and Compression Stimulation on Tissue-Engineered Cartilage - A Finite Element Study Validated by Measurements in a Bioreactor

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Introduction

Adult cartilage has a limited healing capacity. To repair damage resulting from injury or disease, different approaches have been introduced. One of these is tissue engineering (TE). However, so far the properties of scaffold-free TE cartilage are considerably limited. Mechanical stimulation has been shown to improve the quality of TE cartilage but the mechanism is not fully understood [1].

The aim of this study was to determine the local mechanical conditions within TE cartilage tissue subjected to shear and compressive loading. It is hypothesized that the local internal mechanical stimuli influence the collagen fiber alignment.

Materials and methods

A 3D half model consisting of four parts (TE cartilage, hydroxyapatite carrier, agarose ring and loading punch; Fig. 1a) was developed in ABAQUS (Simulia, Providence, RI). This model represents the setup in the experimental bioreactor testing of TE cartilage cultivated on a HA carrier embedded in an Agarose ring (Fig. 1b). Cartilage and agarose ring were meshed with poroelastic 20-nodes-brick-elements, carrier and loading punch were modeled as rigid bodies. Since the cartilage adheres to the carrier and agarose ring, respective translational movement was constrained ($\Delta x = \Delta y = \Delta z = 0$). The friction coefficient between cartilage and agarose ring and loading punch was set to $\mu = 0.06$ (own measurements). The poroviscoelastic (cartilage) and poroelastic (agarose ring) input parameters were either calculated directly from experimental data or indirectly using simulations and optimization algorithms (Young's modulus E , permeability k , Poisson's ratio ν , time constant τ , relaxation modulus G).

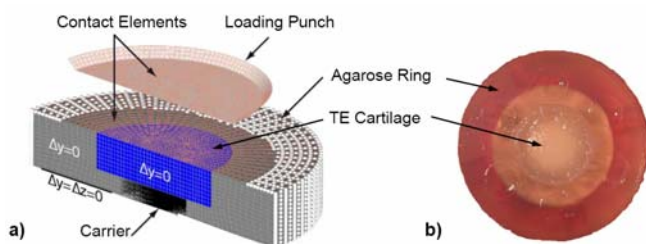


Fig. 1: (a) 3D half model of cartilage implant embedded in an agarose ring with boundary conditions (b) Top view of TE cartilage with agarose ring.

Two types of loadings were simulated moving the loading punch: (1) 10% cyclic compression at 1 Hz, and (2) +/- 2mm cyclic shear under 10% static compression at 0.25 Hz. The resulting strain distribution as well as the fluid flow were analyzed.

The distribution of collagen fiber alignment from histological sections of experimentally stimulated TE cartilage under similar conditions was compared to the respective simulation results.

Results

Highest strains were tensile and appeared at the loading punch and in the lower cartilage regions towards the boundary areas (Fig. 2b+c). Histological, fiber alignment was mostly observed in the center of the cartilage (Fig. 2a). Under shear loading additionally a horizontal fiber alignment close to the loading punch was observed (not shown).

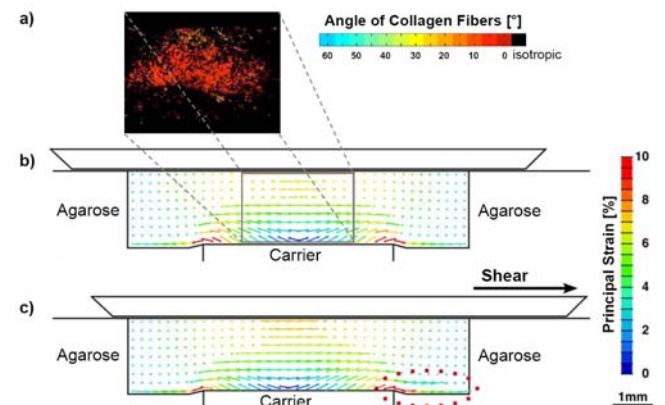


Fig. 2: (a) Histology: Collagen fiber alignment of stimulated cartilage. Shown is the center section of the cartilage (b+c) Simulation: Principal strains within the tissue when compression or shear is applied. Note that the color bar represents collagen fiber angles for part (a) and principal strain for part (b+c).

Discussion

Provided that alignment of collagen fibers depends on tensile strain, a horizontal alignment is predicted mainly in the center and the upper region of the cartilage as well as in the lower cartilage regions towards the boundary areas. Histological a horizontal alignment, however, was mainly found in the centre of the cartilage only. The direction of fluid flow (not shown) does not give a conclusive explanation of the alignment of collagen fibers either.

Compression and tensile strains under the loading punch were 30-50% higher than the compression amplitude. It could be speculated that the strains in the center of the cartilage, where a good agreement between model and experiment was found, were appropriate to achieve fiber orientation along the direction of the principle strains. Possibly strain direction and strain magnitude together determine collagen fiber orientation.

The FE Model used in this study neglects many of the parameters that have an effect on the chondrocytes. It only models the effect of mechanical stimulation on tissue strain and fluid flow in TE cartilage. Presently the model does not fully explain the collagen alignment observed experimentally, which could also be due to the loading magnitude chosen in the experiment.

References

[1] Waldmann *et al.* Eur Cell Mater 2007