Modeling of solute Transport in cartilage under static and dynamic loading

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INTRODUCTION

Articular cartilage consists mostly of chondrocytes and an extracellular matrix, the latter being composed of water, collagen fibers and proteoglycan. Since adult cartilage is avascular, the only way chondrocytes receive nutrient and get rid of waste is by diffusive/convective transport across the articular surface. During its daily routine, cartilage is subjected to a wide range of static and dynamic loading. Osteoarthritis is characterized by a deterioration of cartilage: it is believed that type and intensity of the mechanical loading play a major role in regulating transport activity and, therefore, degeneration. Previous theoretical studies of solute transport in cartilage assumed constant diffusion coefficient; in the present work we relax this assumption.

In this study, a mixture theory based, three dimensional formulation of neutral solute transport in soft tissue is presented [1]. By using Cohen-Turnbull-Yasuda's tortuosity model [2], the diffusion coefficient is made to depend on local deformation. Employing this model, we then study the effects matrix structure, solute size, and the type and intensity of mechanical loading have on the solute transport in soft tissue.

METHODS

We model the tissue as a three phase mixture, consisting of an interstitial fluid, a hyperelastic solid matrix, and a neutral solute. The governing equations for neutral solute transport in cartilage are derived from the conservation of linear momentum, mass of each phase and the mixture. The conservation equations are complemented with the various constitutive equations.

Under appropriate circumstances, the governing equations reduce to the classical convection/diffusion equation and the equations of the biphasic cartilage model. The 3-D formulation is then implemented in the finite element code ABAQUS, following Ferguson[3]. Since convective diffusion is analogous to convection/diffusion of heat, the third equation in the formulation is solved by thermal analogy procedure in ABAQUS.

RESULTS AND DISCUSSION

We validate our model for diffusion of solute in cartilage with Quinn's experimental data[4], as shown in Figure1. Curves represent our model, and symbols represent the experimental data. Quinn's experiments were performed on solute transport in cartilage under unconfined compression.

Confined compression tests are selected to show the application of our theoretical model (Figure2). 400Da and 400kDa dextran transport are investigated. Solute diffuses from the surface into the deep layer of the tissue. Figure2 shows concentration distribution of the solute in the cartilage (through the depth) after 1h diffusion into the tissue under 0%,10% and 20% static compression.

The Y coordinate represents the normalized reduction of concentration when the compression of the tissue varies from 0% to 10% or 20% of its intact thickness. For both solutes, the static loading inhibits their diffusion. 400kDa diffusion shows a higher reduction with increasing loading.

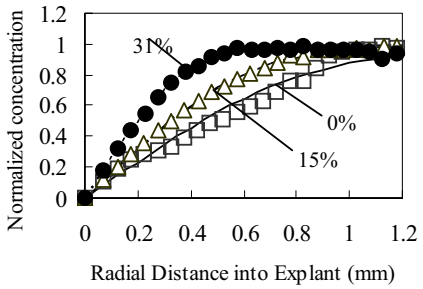

Figure 1. Concentration distribution of 40kDa under static loading (0%, 15%, 30% compressive strain)

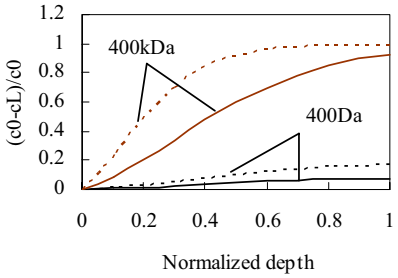

Figure 2: Concentration distribution, static loading : — 10%compressive strain---20%compressive strain

CONCLUSIONS

We propose a three phase mixture model on a 3-D finite element platform to predict the diffusive and convective transport of different size solute in cartilage under different mechanical loading.

REFERENCES

1. Rajagopal KR, et al. *Mechanics of Mixtures*, 1995.
2. Yasuda H, et al. *Makromolekular Chemie***118**, 19-35, 1968.
3. Ferguson SJ, et al. *J Biomech* **37**, 213-221, 2004.
4. Quinn TM, et al. *J Bioche. Biophys Methods* **52**, 83-95, 2002.