European Cells and Materials Vol. 12. Suppl. 1, 2006 (page 19) ISSN 1473-2262

Multiscale Finite Element Modeling in Tissue Engineering of Articular Cartilage

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INTRODUCTION: Mechanical loading can impact the process of extracellular matrix (ECM) formation in tissue engineering (TE) of cartilaginous constructs for articular cartilage repair. The determination of the most effective type of loading, the appropriate load history, and the mechanical field variables responsible for the stimulation of cell activity is still subject of contrary discussions and motivation of numerous investigations. Numerical approaches like the finite element method (FEM) may become a powerful tool, and provide useful hints for more efficient TE processes.

METHODS: To analyze the hydrated and complex composite structure of hyaline cartilage we propose a biphasic, poroelastic model considering the interactions between solid and fluid phase of the tissue. Further, we assume an anisotropic, elastic solid matrix with tension-compression nonlinearities and rate dependent stiffening due to viscoelastic effects of the solid phase.

Following an idea of Guilak and Mow [1] to determine the mechanical loading conditions for a single cell, and deducing from the cell response the prediction of local cell stimulation, a multiscale FE approach has been chosen. Starting with a macro-scale FE model of the native tissue or the TE construct the local load history of a selected element of this FE mesh provides the boundary conditions for a micro-scale FE model with a single cell and its neighborhood.

The material model mentioned above has been implemented into a commercial FE-code. Effects of variations in boundary conditions, loading regime and material properties on the evolution of mechanical field variables in the tissue and the mechanical loading of a single cell have been obtained [2]. Those were compared against the spatial distribution of cell messages of TE constructs [3].

RESULTS: It was shown that the fluid flow and the distribution of the pore pressure as well as its gradient essentially influenced mRNA expression. Thereby, the permeability of the construct plays a major role. The dependency on load velocity in the range of frequencies under consideration is less distinct.

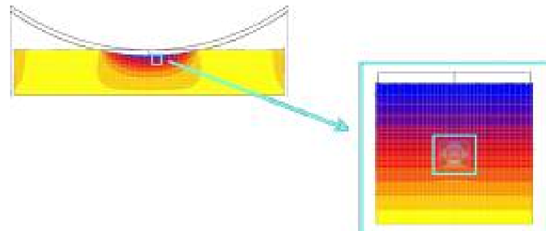

Fig. 1: Multiscale finite element approach. Macromodel: Compressed disc of native cartilage or seeded scaffold (left). Micromodel: Single cell with adjacent region of ECM (right).

DISCUSSION & CONCLUSIONS: In conclusion, the results suggest that the mechanical properties of the scaffold need to function in concert with the experimental concept of the bioreactor to successfully generate cartilaginous tissue. A multi-scale finite element model has been presented as the essential part of a tissue engineering strategy. A macro-scale model is designed to investigate mechanical conditions of native and tissue engineered cartilage as well as tissue property changes in a bioreactor, while a micro-scale model will be used to determine the stress and strain fields in a chondrocyte and in its local mechanical environment. Modeling will be continuously adapted to biochemical and biomechanical data.

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ACKNOWLEDGEMENTS: This work was supported by AO Research Grant 02-W66.