Effect of Cartilage Endplate on Cell Based Disc Regeneration: A Finite Element Analysis

INTRODUCTION

The intervertebral disc (IVD) is the largest cartilaginous structure in the human body that allows for flexation and extension in the human spine. Studies have shown that disc degeneration has been strongly linked to low back pain. Poor nutrient supply has been suggested as a potential mechanism for disc degeneration. The cartilage endplate (CEP) was found to be one of the main pathways for nutrient supply to the IVD. Therefore, the effect of calcification of the cartilage endplate on nutrient distribution inside the human IVD needs to be analyzed. Furthermore, injection of IVD cells in the NP region was used in cell based therapy in low back pain treatment. The nutrient factor could play significant role in this procedure. Therefore, the objective of this study was to examine the effects of endplate calcification and injection of IVD cells on the nutrient distributions inside the human IVD under physiological loading conditions using multiphasic finite element modeling.

METHODS

The IVD was modeled as an inhomogeneous material with annulus fibrosus (AF), nucleus pulposus (NP), and CEP (Figure 1, a). Responses of physical significance and nutrient transport in the human IVD disc under physiological loading (compression at day time and recovery at night, Figure 1, b) were analyzed in this study. The thickness of the disc and endplate were 10 mm and 0.6 mm. The effect of endplate calcification on nutrient solute transport was investigated. The water content of normal and calcified endplate is set as 0.60 and 0.48. The cell density in the NP region is increased by 50%, 100%, and 150% in order to analyze nutrient factors in the cell based treatment for low back pain caused by injection of IVD cells. In this study, the human disc was modeled as an isotropic inhomogeneous mixture consisting of an intrinsically incompressible elastic solid (with fixed charge), water, ions (Na+ and Cl−), and nutrient solute (oxygen, lactic acid and glucose) phases. A theoretical model [1] based on the triphasic theory [2] was used in this study. Strain-dependent hydraulic permeability and solute diffusivities were considered using the constitutive relations for the AF and gels [3]. The Michaelis-Menten equation was used to describe the association between the oxygen consumption rate, oxygen concentration, and pH value. Maximum oxygen consumption rate \( v_{\text{max}} \) is 5.27 nmol/million cells/hr for NP cells and 3.64 nmol/million cells/hr for AF cells. Michaelis-Menten constant \( k_{\text{mNP}} \) is 3.4 \( \mu \)M for NP cells and 12.3 \( \mu \)M for AF cells. The production rate of lactic acid is also coupled with oxygen concentration and pH value [4]. The consumption rate of glucose is half that of the lactic acid production rate.

RESULTS

From Figure 2, there is no significant difference in nutrient distribution inside the IVD at morning and night. Oxygen and glucose concentrations are lower in the disc with the calcified cartilage endplate compared with the disc with the normal endplate. On the contrary, lactic acid concentration is higher in the disc with the calcified endplate. The increase in cell density in the NP region significantly decreases the extreme oxygen and glucose concentrations (lowest concentration inside the disc), while increasing the extreme lactic acid concentration (highest concentration inside the disc), Figure 3. The effect on the glucose concentration was most significant in the disc with the calcified endplate compared to the discs with a normal endplate and thin calcified endplate. Specifically, the extreme glucose concentration reaches zero in the AF region in the disc with the calcified endplate when cell density in the NP region is increased by 50%. By contrast, effect on oxygen and lactic acid concentrations in the disc with the normal endplate, calcified endplate and thin calcified endplate (Thickness of CEP above NP region is decreased by half) are similar, Figure 3.

DISCUSSION

No significant differences in nutrient solute concentration profiles inside the disc were found between morning and night. This indicates that nutrient distribution inside the disc maintains stable concentrations under physiological loading. A calcified cartilage endplate significantly blocks nutrient supply to the disc leading to significantly lower oxygen and glucose concentrations and higher lactic acid concentration inside the human IVD. Increasing the cell density in the NP region could increase cellular metabolism, therefore causing nutrition deterioration in the human IVD, specifically the glucose concentration in the disc with the calcified endplate. The effect is less significant in the disc with thin calcified endplate. This suggests that change of cellular metabolism caused by injection of IVD cells needs to be addressed in cell based therapy for low back pain.

SIGNIFICANCE

This study helps to understand the pathology of IVD degeneration and could provide guidance for cell based therapy for low back pain.

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REFERENCE


Figure 1. (a) 3D view of human lumbar IVD model and (b) cyclic loading on the top and bottom of the disc.

Figure 2. Nutrient distribution [oxygen (kPa), lactic acid and glucose [nM]] inside human IVD in the morning and before sleep: (a) \( x \) axis from center to periphery and (b) \( y \) axis from posterior to anterior.

Figure 3. Effect of increase in cell density on normalized extreme nutrient concentration inside human IVD. Cell density in NP region is increased by 50%, 100%, and 150%.