Effect of Load Frequency on the Trans-endplate Transport of Nutrients to the Intervertebral Disc.

Mitul A. Shah¹, Hongqiang Guo, PhD¹, Eric Ledet, PhD², Juergen Hahn, PhD¹.
¹Rensselaer Polytechnic Institute, Troy, NY, USA, ²Tbd, Tbd, VA, USA.

Disclosures: M.A. Shah: None. H. Guo: None. E. Ledet: None. J. Hahn: None.

Introduction: Intervertebral discs (IVDs) are heterogeneous, fibrocartilaginous cushions serving as the spine's shock absorbing system protecting the vertebrae, brain and nerves. According to the American Spine Decompression Association (ASDA), lower back pain is closely associated with degeneration of the IVD affecting nearly 80% of the population at some point during their life. The degeneration of the intervertebral disc is a cascading event that is often attributed to the cumulative damage caused by ageing, injury, diseases such as osteoarthritis, heavy physical work, lifting, stationary work postures and vibrations. The IVD is one of the largest avascular, charged, hydrated soft tissues in the body and hence depends primarily on the end plates for nutrients. The interaction between negatively charged proteoglycans in the extracellular matrix and positively charged ions gives rise to physiochemical, electro-kinetic effects such as Donnan osmotic pressure, swelling, and negative osmosis [1]. The transport of fluid and solutes in the IVD, which depend upon the physiochemical factors, such as water content, and fixed charge density, need to be considered in a computational model. Hence it is essential to quantify the transport behavior of IVD to predict factors that could increase transport of nutrients, in this study Na+ and Cl- ions, to the IVD. Specifically, we investigate in this study if cyclic loading can augment trans-endplate transport and enhance the regenerative potential of the IVD.

Methods: A cylindrical disc of tissue (thickness 0.5 mm) is placed inside a confining cylinder for displacement controlled, mechanical load testing. The biphasic swelling theory developed by Wilson et al. [2] was implemented in COMSOL Multiphysics. To validate the implementation, the stress-relaxation behavior of the IVD under confined compression was modeled and the results were compared with the triphasic model [1]. In the frequency analysis, the model was subjected to sinusoidal loading (Fig 1.b), for 300 seconds, at a frequency ranging from 0.01 Hz to 1.6 Hz. Two sets of material properties were studied: (1) homogeneous material properties; and (2) the depth and strain dependent porosity and permeability [3]. The total flow of nutrients across the top boundary for each frequency was calculated from the resulting ion concentration profile.

Results: The Na+ concentration profiles for different times, for both the models, during the compression and relaxation stage were observed to be accurate in trend and magnitude when compared with the triphasic model [1] (Fig 2), similar results were observed for the concentration profiles for Cl- for different times. The total computed ionic flow increases linearly with frequency for the biphasic swelling model while the depth dependent biphasic swelling model exhibited a more non-linear relationship (Fig 3 and 4).

Discussion: The biphasic swelling model assumed that material properties are homogeneous throughout the disc and, as a result, the ionic fluid flow increases linearly with the frequency. In comparison, the depth dependent biphasic swelling model assumes that the disc is most porous at the top boundary resulting in a higher, non-linear ionic fluid flow with frequency. Force controlled experiments usually show that the total ionic flow decreases due to solid matrix stiffening at higher frequencies. This however is not observed in the described models as the reaction forces generated by the applied displacement are significantly lower and thus no matrix stiffening is observed.

Significance: No prior research has been done on the impact of loading frequency on the trans-endplate transport. This study demonstrated that loading frequency significantly affects transport across the endplate and can play an important role in treatment of disc degeneration.

Acknowledgments:

Figure 1: Schematic for a.) confined compression stress relaxation test, b.) frequency analysis

Figure 2: a.) Na$^+$ concentration at different times during the compression stage and b.) during the relaxation stage computed by the triphasic model. c.) Na$^+$ concentration at different times of compression and relaxation stage computed by the biphasic swelling model. d) Na$^+$ concentration at different times of compression and relaxation stage computed by the depth dependent biphasic swelling model.