Biphasic Mechanical Properties of Poly(vinyl alcohol) Hydrogels for Cartilaginous Tissue Replacement

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INTRODUCTION: Poly(vinyl alcohol) (PVA) hydrogels prepared using freezing and thawing techniques have great potential for cartilaginous tissue replacement, such as articular cartilage and intervertebral disc [1]. Several studies have been done to characterize the mechanical properties of PVA hydrogels. However, there are no data available for the biphasic mechanical properties of these materials. Cartilage mechanical behavior can be well predicted by the biphasic theory developed by Mow and co-workers [2], and the intrinsic biphasic properties of cartilaginous tissues are well-documented in the biomechanics literature. Thus, the objective of this study was to determine the biphasic mechanical properties, such as aggregate modulus and hydraulic permeability, of PVA hydrogels using unconfined and confined compression tests. The effect of freezing/thawing cycle on the material properties was also investigated.

METHODS: Aqueous solutions of 17.5 wt % PVA were prepared by dissolving PVA (Mw=124,000-186,000) in deionized water for 0.5h in an autoclave. The prepared aqueous solutions were cast in a mold with 15mm diameter and 2.5mm thickness. The samples were exposed to one to twenty cycles of freezing for 16h at -20°C and thawing for 8h at room temperature. Cylindrical specimens (5mm diameter) were excised from hydrogel disc using a corneal trephine. The equilibrium stress-strain relationship for each plug in unconfined compression was determined on an ELF 3200 (EnduraTEC, MN) (Fig.1a). The equilibrium modulus was calculated in the linear stress-strain region. For small deformation, this calculated modulus can be considered as the Young's modulus *E*. A new confined compression chamber was designed for this study (Fig. 1b). Initially, a 10% offset strain was applied to the specimen. After reaching equilibrium, a ramp displacement to 5% strain was applied at the rate of $0.001 s^{-1}$, and the reaction force was recorded by the load cell for 2 hours. The biphasic material properties of hydrogel (i.e. aggregate modulus H_A and hydraulic permeability k) were obtained by curve-fitting stress-relaxation data to the biphasic theory.

RESULTS: The equilibrium modulus of the PVA hydrogel increased dramatically during the first 6 freezing/thawing cycles (Fig.2). After 8 cycles, the number of freezing/thawing cycle showed no significant effect on the equilibrium modulus. The hydraulic permeability coefficient and aggregate modulus of 6-cycle as well as 8-cycle hydrogels were determined. A good agreement was shown between the biphasic theoretical prediction and the experimental results. Increasing the number of freezing/thawing cycles increased the aggregate modulus and decreased permeability of PVA gels (Table 1). Note that shear modulus and Poisson's ratio of the hydrogel were calculated from the measured aggregate modulus and Young's modulus (i.e. unconfined equilibrium modulus).

DISCUSSION: It is apparent that the aggregate modulus of PVA gels are comparable to the values of human cartilage and annulus fibrosus, suggesting that PVA gels have sufficient equilibrium strength for cartilage tissue replacement. Nevertheless, the hydraulic permeability of hydrogels is one magnitude higher than human cartilage. The interstitial fluid flow within the hydrogel/cartilage, which plays a fundamental role in the loading supporting mechanism, is mainly governed by the hydraulic permeability. The higher permeability of hydrogels means the lower response of fluid pressurization to the mechanical loading. Therefore, in the future, the mechanical properties of PVA hydrogels need to be further enhanced for cartilaginous tissue replacement.

REFERENCES: [1] Hassan CM and Peppas NA, 2000, Advances in Polymer Science, 153:37-65. [2] Mow VC et al, 1980, J Biomech Eng, 102:73-84. [3] Mow VC and Hayes WC, 1997, Basic Orthopaedic Biomechanics, Lippincott-Raven, New York. [4] Elliott DM and Setton LA, 2001, J Biomech Eng, 123:256-263.

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Figure 1: Test configuration of unconfined compression (a) and confined compression (b).

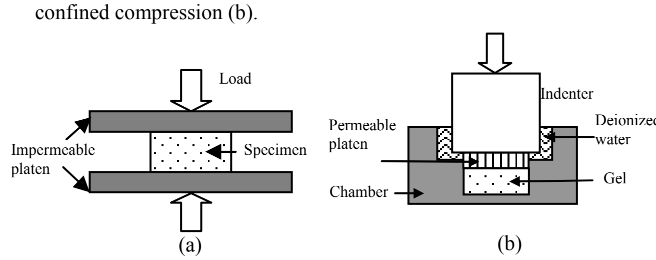

Figure 2: Effect of freezing/thawing cycle on unconfined equilibrium modulus (i.e. Young's modulus).

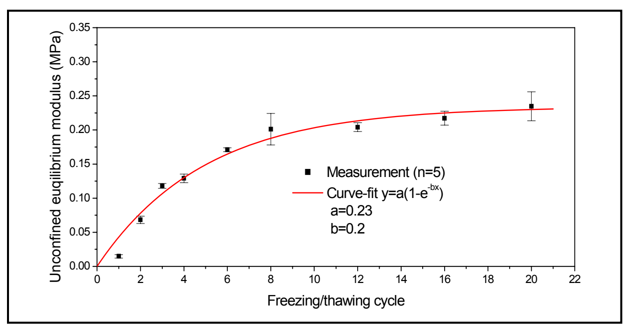

Table 1: Biphasic material properties of PVA hydrogels (mean, n=5), articular cartilage and annulus fibrosus (AF).

	PVA gel 6-cycle	PVA gel 8-cycle	Human cartilage [3]	Human AF[4]
Aggregate modulus (MPa)	0.29	0.32	0.53~0.70	0.50
Shear modulus (MPa)	0.063	0.074	0.24~0.31	0.15
Poisson's ratio	0.36	0.35	0.10	0.28
Permeability ($\times 10^{-14} m^4/Ns$)	3.59	3.32	0.12~0.22	0.15