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Relationship between streaming potential and compressive stress in bovine intervertebral tissue

Kazuhiro Fujisaki*, Shigeru Tadano, Nozomu Asano

Division of Human Mechanical Systems and Design, Faculty of Engineering, Hokkaido University, Kita-13, Nishi-8, Kita-ku, Sapporo 060-8628, Japan

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ABSTRACT

The intervertebral disc is formed by the nucleus pulposus (NP) and annulus fibrosus (AF), and intervertebral tissue contains a large amount of negatively charged proteoglycan. When this tissue becomes deformed, a streaming potential is induced by liquid flow with positive ions. The anisotropic property of the AF tissue is caused by the structural anisotropy of the solid phase and the liquid phase flowing into the tissue with the streaming potential. This study investigated the relationship between the streaming potential and applied stress in bovine intervertebral tissue while focusing on the anisotropy and loading location. Column-shaped specimens, 5.5 mm in diameter and 3 mm thick, were prepared from the tissue of the AF, NP and the annulus–nucleus transition region (AN). The loading direction of each specimen was oriented in the spinal axial direction, as well as in the circumferential and radial directions of the spine considering the anisotropic properties of the AF tissue. The streaming potential changed linearly with stress in all specimens. The linear coefficients k_e of the relationship between stress and streaming potential depended on the extracted positions. These coefficients were not affected by the anisotropy of the AF tissue. In addition, these coefficients were lower in AF than in NP specimens. Except in the NP specimen, the k_e values were higher under faster compression rate conditions. In cyclic compression loading the streaming potential changed linearly with compressive stress, regardless of differences in the tissue and load frequency.

1. Introduction

The spine is formed by a series of vertebrae and intervertebral discs in addition to muscles and ligaments. The biological function of the intervertebral discs is to provide motion flexibility and stiffness to support the body weight. Intervertebral disc tissue is classified into either nucleus pulposus (NP) or annulus fibrosus (AF). NP is located in the centre of the tissue and surrounded by a layer forming the AF. The AF contains numerous collagen fibres that are composed of concentric layers encircling the NP. The collagen fibres are oriented in layers that intersect with each other (White and Panjabi, 1978). Urban and Maroudas (1979) stated that the NP contains much more liquid than the AF. Understanding the interplay between applied stress in human motion for a variety of situations and body weights is important to the analysis of injuries of this tissue. Many types of stress/strain analyses of the spine have been carried out to explain the mechanical properties of biological soft tissue, and a number of physical models have been proposed in analytical studies. In these models, the properties are described on the basis of their approximate elasticity or viscoelasticity (Bilston and Thibault, 1996; Ichihara et al., 2003). In addition, there are biphasic models that consider the interaction of the solid and liquid phases (Ateshian et al., 1997; LeRoux and Setton, 2002; Perie et al., 2004). When the phases become deformed the liquid phase in the tissue flows out through openings in the solid phase, and the interaction and friction between the two phases give rise to macroscopic viscoelastic behaviour. In addition, the solid phase of soft tissue contains a large amount of negatively charged proteoglycan, which is caused by glycosaminoglycan having negatively charged sulphate and carboxyl groups. Strain in the soft tissue changes the charge density of the proteoglycan and disrupts the balance of the electrochemical equilibrium. This electrical charge affects the viscoelastic deformation of the tissue. The triphasic theory was proposed to describe the mechanical properties of articular cartilage (Lai et al., 1991; 2000; Gu et al., 1993; Ateshian et al., 2004; Sun et al., 2004) while considering the solid and the liquid phases as well as the negative ion phase. When an electrical potential is present in the deformed tissue, the potential changes with the liquid flow. This relative change due to electrical potential is referred to as streaming potential. The streaming potential has been measured in articular cartilage (Frank et al., 1987a; Frank and Grodzinsky, 1987b; Chen et al., 1997; Garon et al., 2001), lumbar discs (Gu et al., 1999), tendons

* Corresponding author. Tel./fax: +81 11 706 6396.
E-mail address: fujiwax@eng.hokudai.ac.jp (K. Fujisaki).

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