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Oscillatory Compressional Behavior of Articular Cartilage and Its Associated Electromechanical Properties

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The compressive stiffness of articular cartilage was examined in oscillatory confined compression over a wide frequency range including high frequencies relevant to impact loading. Nonlinear behavior was found when the imposed sinusoidal compression amplitude exceeded a threshold value that depended on frequency. Linear behavior was attained only by suitable control of the compression amplitude. This was enabled by real time Fourier analysis of data which provided an accurate assessment of the extent of nonlinearity. For linear viscoelastic behavior, a stiffness could be defined in the usual sense. The dependence of the stiffness on ionic strength and proteoglycan content showed that electrostatic forces between matrix charge groups contribute significantly to cartilage's compressive stiffness over the 0.001 to 20 Hz frequency range. Sinusoidal streaming potentials were also generated by oscillatory compression. A theory relating the streaming potential field to the fluid velocity field is derived and used to interpret the data. The observed magnitude of the streaming potential suggests that interstitial fluid flow is significant to cartilage behavior over the entire frequency range. The use of simultaneous streaming potential and stiffness data with an appropriate theory appears to be an important tool for assessing the relative contribution of fluid flow, intrinsic matrix viscoelasticity, or other molecular mechanisms to energy dissipation in cartilage. This method is applicable in general to hydrated, charged polymers.

Introduction

Articular cartilage is the dense connective tissue that functions as a bearing material in synovial joints. It is composed of aqueous electrolyte (~80 percent) and an organic matrix of collagen, proteoglycans, glycoproteins, lipids, and cells. The relatively high content of proteoglycans in normal articular cartilage (~25 percent dry weight) gives this tissue a large osmotic swelling pressure. In humans, the peak forces across hip and knee joints may reach several times body weight [1]. It is believed that articular cartilage can significantly reduce contact stresses in joints, and that cartilage can protect bones from rapidly applied impact loads [1]. Osteoarthrosis, however, can lead to an accelerated wear and tear of cartilage [2] resulting in its eventual destruction and joint dysfunction. During the past few decades, many investigators have focused on the relation between the biomechanical and biochemical events that are associated with this degenerative process. In particular, the role of the proteoglycan, glycoprotein, and collagen components and the interactions between these components in normal and pathological cartilage has received much attention. It is now widely believed that the physical, chemical, and biological properties of cartilage are closely linked to each other in normal and diseased states.

Articular cartilage can be considered a porous gel of proteoglycan aggregates embedded in a water-swollen network of collagen fibrils. When cartilage is compressed, its interstitial fluid is forced to flow relative to the solid organic matrix and to be exuded from this matrix. The frictional drag caused by relative fluid flow, as well as the intrinsic modulus of the solid matrix, contributes to the effective stiffness that cartilage presents to a time-varying load [3].

In this paper, we describe the simultaneous measurement of dynamic compressional stiffness and dynamic streaming potential of bovine articular cartilage. Our experimental procedure has been developed in order to address several unresolved issues in the rheological characterization of cartilage. The first goal, as stated by Woo [4], is the need to obtain fundamental material properties of cartilage for the interpretation of theoretical and experimental data. To our knowledge, there have been no detailed studies of the dynamic compressional properties of cartilage over the wide frequency range 0.001 to 20 Hz, which includes high frequencies relevant to impact loading. We have found that dynamic sinusoidal measurements are useful, in particular, for highlighting the electromechanical behavior of cartilage. Hence, our second goal was to assess the importance of proteoglycans and their associated electromechanical forces to the stiffness and permeability of articular cartilage. We compared the stiffness of normal cartilage to cartilage whose proteoglycans had been

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