Theoretical Analysis of Fluid Pressure Response to Cyclic Loading in Cylindrical Trabecular Bone Modeled as Poroelastic Material

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ABSTRACT

Trabecular bone is a microstructural component of cancellous bone, forming a three-dimensional network structure. The typical individual trabecula is regarded as a cylindrical porous material which is composed of a calcified bone matrix and interstitial fluid in a lacuno-canalicular porosity. For a physiological range of activities excluding shocks, trabeculae *in vivo* are usually subjected to low-frequency cyclic loading due to locomotion and the maintenance of posture. A number of experimental and theoretical studies have shown that the flow of interstitial fluid caused by deformation of the bone matrix under external loading plays an important role in cellular mechanosensing to initiate bone remodelling [1].

In order to quantitatively evaluate the interstitial fluid flow in bone tissue, poroelastic theory formulated by Biot has been widely used [2]. Poroelasticity is a continuum theory that considers the coupling behavior between the elastic solid matrix and the fluid-filled pores. In our previous study, we derived a closed-form solution for the fluid pressure in a two-dimensional poroelastic slab subjected to cyclic loading [3, 4]. However, this solution is insufficient to describe the mechanical behavior of interstitial fluid in a three-dimensional trabecula.

The purpose of this study is to investigate the fluid pressure response to cyclic loading in a cylindrical trabecula based on a poroelastic approach. We developed an analytical solution for the interstitial fluid pressure in a single trabecula by solving the governing equations in the cylindrical coordinate system with the help of the Laplace transformation technique. The obtained solution contained both transient and steady-state responses depending on the loading frequency. The calculated results showed that the transient stage decayed within the first period of cyclic loading. In the steady state, the fluid pressure gradient around the trabecular surface was larger than that around the central axis of trabecula. Furthermore, the fluid pressure gradient close to the surface built up with the increase in the loading frequency. These results suggest that bone cells embedded in the neighborhood of the trabecular surface are significantly stimulated by the load-induced interstitial fluid flow, and the loading rate is one of the essential factors that can influence the process of cellular mechanosensing.

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