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Mathematical modeling of trabecular bone remodeling induced by osteocytic response to interstitial fluid flow

Bone is a load-bearing tissue that can adapt its internal structure and outer shape by remodeling to a changing mechanical environment. The morphological changes in the trabecular microstructure are realized by the coupling of osteoclastic bone resorption and osteoblastic bone formation. It is widely believed that the metabolic activities of these executive cells are regulated by a mechanosensory system of osteocytes buried in the extracellular bone matrix, forming a three-dimensional intercellular network through cellular processes in lacuno-canalicular porosity [1]. The small space surrounding the osteocytes in the porosity is filled with interstitial fluid. When the bone is subjected to dynamic loading, bone matrix deformation induces an interstitial fluid flow [2]. The fluid flow in the lacuno-canalicular porosity seems to mechanically activate the osteocytes and serve as the prime mover for bone remodeling, as well as transport cell signaling molecules [3]. To understand the mechanism of bone functional adaptation, it will be useful to propose a theoretical framework of trabecular bone remodeling that interconnects the microscopic cellular activities to the macroscopic morphological changes through the mechanical hierarchy. In this study, first, we constructed a mathematical model for trabecular bone remodeling, taking cellular mechanosensing and intercellular communication into consideration [4]. This model assumes that osteocytes respond to fluid-induced shear stress and deliver their mechanical signals to the surface cells by intercellular communication. The mechanical behavior of a trabecula with lacuno-canalicular porosity is modeled as a poroelastic material to evaluate the interstitial fluid flow under mechanical loading. Second, on the basis of the proposed mathematical model, we simulated morphological changes in a single trabecula under cyclic uniaxial loading with various frequencies, which is thought to be a significant mechanical factor in bone remodeling. The results of the simulation show the trabecula reoriented to the loading direction with the progress of bone remodeling. As the imposed loading frequency increased, the diameter of the trabecula in the equilibrium state was enlarged by remodeling. Finally, we conducted a remodeling simulation for a cancellous bone cube under monotonously increasing compressive loading, where all the trabeculae are randomly-oriented in the initial geometry. As a result, the degree of trabecular connectivity was gradually decreased and the trabeculae in cancellous bone aligned along the loading direction. These results indicate that our remodeling simulation model can successfully express the macroscopic changes in trabecular morphology from the microscopic cellular activities.

References

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