LACUNA MORPHOLOGY AFFECTS STRAINS IN THE CELL BODY AND DENDRITES, AND ON THE BONE TISSUE

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Introduction

Shape of osteocytes and lacunae varies with bone mechanical stimulation and disease condition. Elongated osteocytes and lacunae have been found in lamellar long bone with a major direction of load [1, 2]. More spherical lacunae have been observed in flat bones [2], woven bone [3], in immature long bones without a prevalent direction of loading [4], but also in long bones with osteopenia [5, 6], osteoarthritis [5] and osteogenesis imperfecta [1]. The aim of this research is to computationally quantify the effect of osteocyte lacuna morphology on (i) the cell body and dendrites mechanics to improve our understanding of osteocyte mechano-sensing, but also on (ii) the surrounding bone tissue strain to determine extracellular matrix (ECM) susceptibility to failure.

Methods

A total of six idealized models were considered for this study and developed in SolidWorks. In three of them, the cell geometry was varied. In these models bone ECM was represented as a cube with 10 channels of 0.6 μm in diameter representing the canaliculi oriented at 45° and 90°. The osteocyte lacunae were inserted inside the bone block and described as a triaxial ellipsoid. The ratio between the minor and major axes, λ, for the three cell models were 0.6, 0.25 (elongated), and 1 (spherical) and the body cell volume was maintained constant among them. The geometry of the osteocyte was offset from each lacuna, allowing for an interstitial fluid space of 0.75μm in thickness [6]. The whole models were then cut to have the same length for the vertical canaliculi. Three more models were implemented to investigate the influence on the cell and ECM strains during loading of (i) the osteocyte lacuna spacing, (ii) the dendrites orientation and (ii) the dendrites number. Thus, in model 4 we doubled the ECM space around the lacuna, in model 5 we oriented the dendrites horizontally and in model 6 we increased to 16 the number of the dendrites. Each model was then imported into Abaqus and meshed with tetrahedral elements. Linear elastic material properties were assigned to the bone (E=11GPa, υ=0.38) and the cell (E=3.1kPa, υ=0.35). Instead, the interstitial fluid space was modelled as a fully saturated poroelastic material (E=40 kPa, υ=0.4, $k_0=4\times 10^{-20}$ m^2 and e=4) [7]. The initial fluid pore pressure was assumed to be zero and imposed on the external surfaces of the interstitial fluid [7]. A sinusoidal displacement of 3000 με (f = 1 Hz) was applied uniformly on the top surface. The nodes on the bottom surface were constrained in the top-down axial direction, allowing for radial displacement.

Results

Results indicate that bone, cell bodies and cell dendrites experience higher maximal principal strain in the spherical cell, compared to the other two more elongated ones. Furthermore, a larger cellular spacing reduces the strains on the cell and ECM, which instead raise in presence of horizontally oriented dendrites and augmented number of dendrites.

Discussion

Our outcomes show that in the spherical model both the cell dendrites and the bone experience higher strain levels. These findings may justify the increased bone turnover and the decreased bone resistance to failure observed in bones with more spherical cells, such as in osteogenesis imperfecta. A larger osteocyte lacuna spacing diminishes the strains in bone and in cell. This is in agreement with previous studies where higher porosity is related to a reduced resistance of bone to failure [9]. This finding on the cell might also clarify why in osteoporosis with lower spherical cell density, there is low bone turnover. When looking at the orientation and the number of dendrites, the models displayed more elevated strains in the cell, with a more homogenous distribution of the strain in the bone. In this context, our results might explain the experimental observations that the increased connectivity and the preferential orientation of the dendrites perpendicular to the cell surface are strategies adopted by the cell to optimize their mechano-sensing, preserving the mechanical environment of the bone. These poroelastic models are the evolution of our earlier studies [8] and combine the advantages of linear elastic and fluid dynamics simulations of the entire cell within the bone, undergoing sinusoidal loading, to provide a more accurate representation of the interstitial fluid space in the osteocyte-canalicular system.

References

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