A numerical model to investigate action of LIPUS in bone healing

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Introduction

Bone is a complex biological tissue with two levels of porosity: the vascular porosity (VP) and the lacuna-canalicular network (LCN). The latter one contains the osteocytes immersed in the interstitial fluid (IFluid). Bone remodeling process is known to proceed all along healing and is notably driven by osteocytes. To speed up or consolidate bone healing, Low Intensity Pulsed UltraSound (LIPUS) is a treatment current in use but biomechanical underlying mechanisms are poorly understood. Our hypothesis is that the ultrasound (US) stimulation at the meso-scale level can induce fluid shear stress acting on osteocytes at micro-scale level, inducing a biological answer. To investigate this question, we developed a relevant numerical model combining acoustics, fluid and structure.

Methods

A 2D finite element model assuming a double-porosity medium was implemented through the commercial software Comsol Multiphysics. The geometrical VP was reconstructed from binarized micro computerized tomography images of fibula. The poroelastic bone matrix including anisotropic structure and LCN filled with IFluid (assumed to be water) was modelled through an equivalent medium (Biot's model). The surrounding soft tissues were assumed to be a fluid water phase. Continuity of pressure and stress fields was imposed as boundary conditions as well as open pore conditions for vascular pores and the endosteum. Periosteum boundary was impervious. US stimulation parameters were chosen from the commercial Exogen device (frequency=1MHz, acoustic pressure=67kPa, transducer diameter=20mm, duty cycle=20% and pulse duration=1ms). IFluid shear stress was calculated as done by [1].

Results and Discussion

IFluid shear stress patterns show peak values at localized locations all around the endosteum and the vascular pores. During one pulse duration, IFluid shear stress ranges from 0 to 10Pa in all the domain. For selected points around endosteum, temporal average values are between 0.2 and 1.3 Pa (see Figure 1). They are in the range of prediction interval (0.3-8 Pa) given in the literature. However, it should be noted that values from [2] were recorded for a physiological loading and thus a stimulation frequency smaller than LIPUS frequency. Further research is currently on progress to investigate if lining cells that are present especially around the endosteum and the vascular pores could be the involved mechanosensors in LIPUS treatment [3]. Other phenomena could be also associated in mechanisms like microstreaming or piezoelectricity.

References

[1] Goulet, GC., et al. (2008) J. Biomech. 41(10), p2169
[2] Weinbaum, S., et al. (1994) J. Biomech. 27(3), p339
[3] Kwon, H., (2010) J Bone Miner Res, 25(8), p 1798

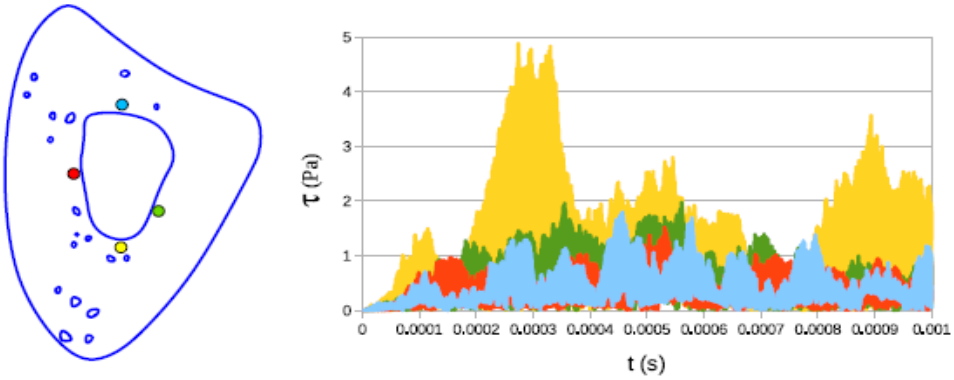

***Figure 1**: Geometrical model with 4 specific locations defined by a color (left); IF shear stress during one cycle for each location (right)*