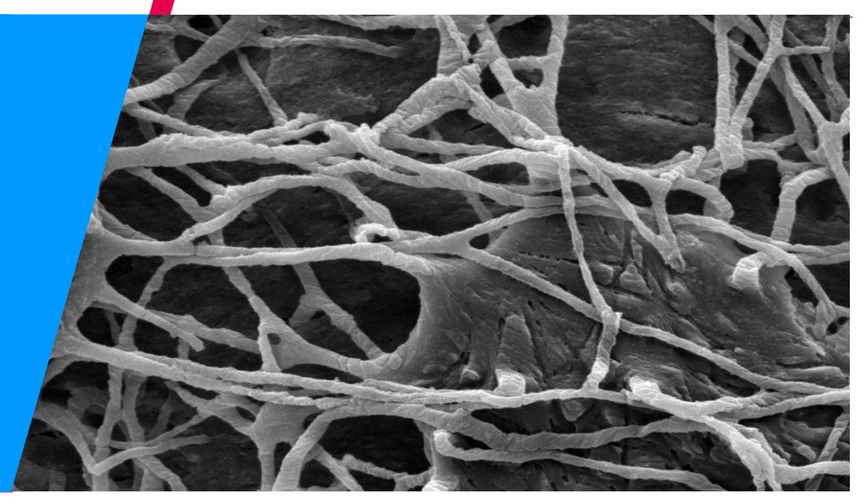
Multiscale approach in bone remodeling process

Orthopaedic Biomechanics

MySpine
Patient-specific spinal treatment simulation

Technische Universiteit Eindhoven University of Technology

Multiscale Approach in Bone Remodeling Process



Michele Colloca, Bert van Rietbergen and Keita Ito

Background

Bone remodeling takes place at the cellular scale where osteoclast cells remove bone tissue and osteoblast cells deposit new bone tissue. It is hypothesized that this process is regulated by osteocyte cells based on local conditions [1-3] and specific surface [4] (Figure 1).

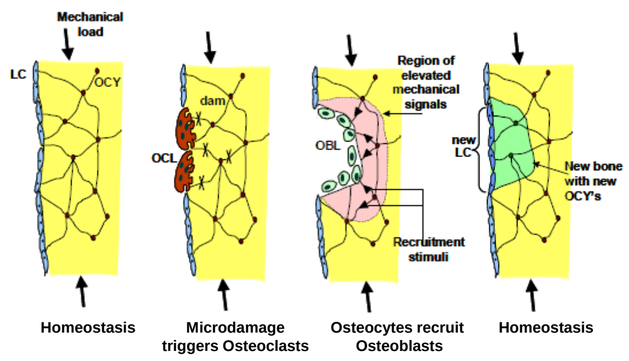


Figure 1. Activation of osteoblast-osteoclast activities under mechanical stimulus [2].

A multiscale approach is needed to describe the effects of bone remodeling at higher scales (e.g. organ level). Therefore, the aim of this study is to develop an analytical model for bone adaptation which includes different spatial and temporal scales in order to predict the evolution of bone volume fraction.

Methods

The rate of change of bone volume fraction in a RVE (Figure 2), modulated by mechanobiological and geometric feedback, can be expressed by:

$$\frac{d(BF)}{dt} = \left[\tau\left(\mu \cdot \frac{MS}{(BF)^{\gamma+1}}\right) - f_{ocl} \cdot V_{res}\right] \cdot \alpha \cdot \frac{2}{R} \cdot BF \qquad \text{Eq.(1)}$$

Bone Apposition Rate (BAR) [mm/day] | Bone Resorption Rate (BRR) [mm/day] | Specific Surface [1/mm]

where τ is the bone formation time constant [mm^3/(nmol/s)day], μ is the osteocyte mechanosensitivity [(nmol/s)/(MPa/s)mm^2], α(=0.8) and γ(=3) are coefficients, MS is the strain energy density rate [MPa/s], f_{ocl} is the osteoclast recruitment frequency [1/day] and V_{res} is the linear resorption per cavity [mm]. A previously developed bone remodeling algorithm based on mechanotransduction [1,2] was used to compare analytical and numerical results.

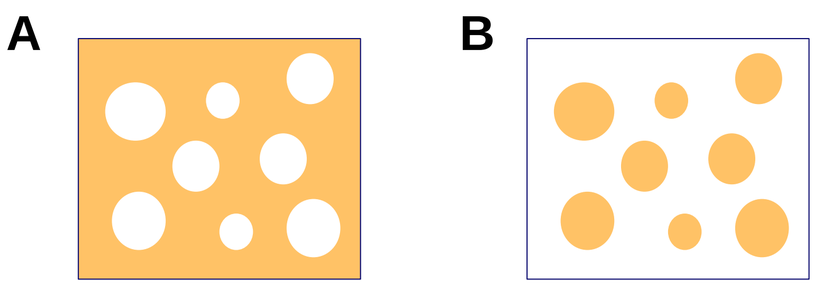


Figure 2. RVE of bone. The voids (A) or the trabeculae (B) are cylindrical, of average radius R and of average length l.

Results

The closed-form solution of Eq. (1) is represented by :

$$BF(t) = \frac{\left\{MS \cdot \mu \cdot \tau + e^{-\frac{8\alpha(f_{ocl} \cdot V_{res}).t}{R}}\left[(f_{ocl} \cdot V_{res}) \cdot BF(0)^4 - MS \cdot \mu \cdot \tau\right]\right\}^{1/4}}{(f_{ocl} \cdot V_{res})^{1/4}}$$

The evolution of bone volume fraction is plotted in Figure 3A,B for two different initial conditions. Theoretical predictions and numerical results show close matching. It follows that the presented analytical model is suitable for guiding the computer simulations of bone microstructures in different loading and metabolic conditions (Figure 3C,D).

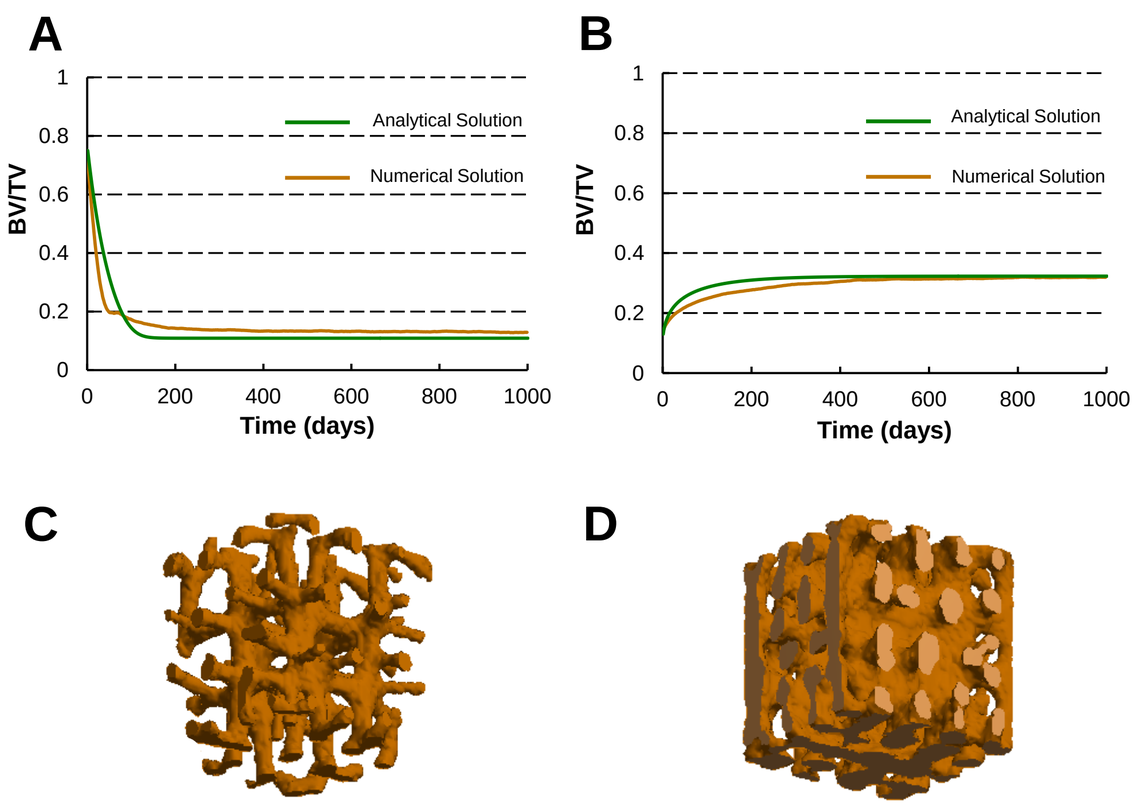


Figure 3. Evolution of bone volume fraction with (A) BV/TV_0 = 0.75 and (B) BV/TV_0 = 0.13 initial conditions. Final trabecular architecture of the RVE after reaching the equilibrium and assuming (C) a value of BV/TV equal to 0.13 and (D) equal to 0.32, respectively.

Discussion

In this study the bone remodeling was modeled as a dynamic process which was driven by mechanical loading and cellular activities. The analytical model allows for investigating the interaction between metabolic and mechanical factors and for studying the effects of nutritional, hormonal and pharmacological therapies in different diseases.

[1] Huiskes R. et al. (2000). Effects of mechanical forces on maintenance and adaptation of form in trabecular bone, Nature, 405:704-706.
[2] Ruimerman et al. (2005). A theoretical framework for strain-related trabecular bone maintenance and adaptation, Journal of Biomechanics, 38:931-941.
[3] Carter DR and Beaupre' GS (2001). Skeletal function and form. Cambridge University Press.
[4] Martin RB, (1984). Porosity and specific surface of bone. CRC Crit. Rev. biomed.Eng. 10: 179-222.

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