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Model of cancellous bone adaptation considering hypermineralized bone tissue

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1 Introduction

Aging and a low physical activity often involve a decrease in bone mass and a mechanical weakening of bone at global scale, increasing fracture risk. In particular, cancellous bone tissue which plays a mechanical role on the overall rigidity and strength of bone organs, is importantly degraded. Numerous computational models have been developed to simulate bone remodelling process and predict over decades the evolution of microstructure of cancellous bone and its mechanical behaviour [1,2]. These models were based on μCT reconstruction of bone samples and consider generally the tissue as a homogeneous material. However bone remodelling is spatially heterogeneous with concomitance of aged and new bone tissue. Moreover mineralization is a process occurring with time leading to heterogeneous mineral concentration and so mechanical properties. To determine the influence of a heterogeneous material on remodelling of cancellous bone, a computational study was performed here on a bone sample reconstructed in 3D from a μ-CT image stack. Heterogeneous material properties were defined depending on mineral density revealed by μCT gray value. The results show that hypermineralization of cancellous bone influences considerably local mechanical behaviour although overall mechanical behaviour was not affected. Besides, bone cells are mechano-sensitive and adapt bone microstructure by resorbing aged or damaged tissue and aposing new one. So, a iterative computation of bone degradation was then performed in case of a low physical activity. Sites which were underloaded were considered as possible sites of remodelling process. This study shows that heterogeneous material properties may influence localization of bone remodelling

This model which analyzes alterations of cancellous bone microstructure may help in the prediction of fracture risk. It can be also implemented so as to predict effect of drug treatment on bone cell activity and the balance between apostition and resorption.

2 Methods

2.1. Trabecular bone sample and μ–CT imaging

We considered a bone sample from human femoral head (woman of 87 year-old). A cubic specimen of 10x10x10mm^3 was scanned with a μ-CT system of 20 μm resolution. A phantom representing the mineral content of a normal mineralized bone tissue was placed under the sample. This latter gave a gray-value reference in order to identify locally material components and the related mechanical properties.

2.2. Finite element model

A first F.E. *heterogeneous model* (4x4x4 mm^3) extracted from cubic sample consisted of 2344910 elements converting voxels into equally sized eight-node brick. All elements were assumed to be linearly elastic and isotropic with Poisson's ratio set to 0.3 and the following power law relationship between Young's modulus and bone grey value :

$$E_{elt}=E_0 . GV_{elt}^{\gamma}$$

where GV_{elt} is the normalized gray-value element, γ a constant exponent set to 1.5 [4], and E_0 was taken to be equal to 19 GPa [5]. In order to compare the influence of material heterogeneities, an *homogeneous model* with constant material properties was also considered. Young's Modulus and Poisson's ratio were equal to 19 GPa and 0.3 respectively. Uniaxial compressive loading of 0.1% was applied to the the cubic sample

2.3. Bone adaptation model

The finite element of cancellous bone is implemented in a algorithm modifying bone structure iteratively and under compressive loading by apposition or resorption.
Some authors considered that when strain stimulus is lower than ε_{res}=100με bone matrix is resorbed. On the contrary, when strain stimulus exceeds ε_{app}=3000με new bone is apposed [7]. Here we considered that if strain energy is lower than w_{res}, bone is resorbed and if it is greater than w_{app} new bone is apposed :

$$w_{res} = \frac{1}{2} E_{bone}. \varepsilon_{res}^2$$
$$w_{app} = \frac{1}{2} E_{bone}. \varepsilon_{app}^2$$

with E_{bone} = 19GPa. When strain energy in a element of the model is outside [w_{res};w_{app}], elements are either deleted or created at bone surface to represent respectively resorption or apposition. New bone tissue was given Young modulus which increased iteratively from 0.5 GPa to 35Gpa to simulate mineralization.

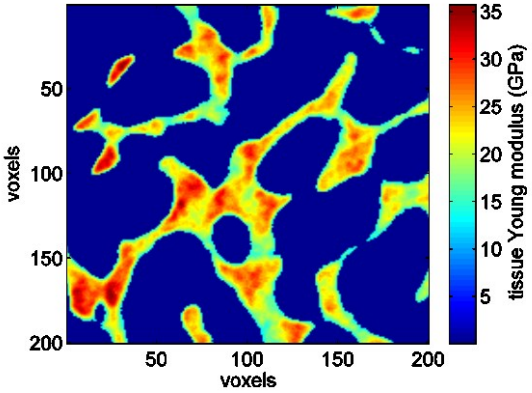

Figure 1 : Young's modulus heterogeneous distribution. Hypermineralized bone tissue in red

3 Results and Discussion

2.2 Influence of hypermineralized bone tissue

Numerical compression tests were performed and Apparent Young's modulus and mean strain energy density were calculated for both previous models. Difference of 7.5% was noted between model with homogeneous material and model with heterogeneous material, which was in agreement with the literature [6]. Nevertheless a difference of 20% of over-constrained bone volume was identified (where strain exceed 3000με). From a biological point of view beyond this threshold new bone tissue is apposed, or in contrary when strains are under 100με bone tissue is removed [7].

2.3 Hypermineralized bone precursor of bone remodeling

Iterative compression tests were simulated on the cancellous bone model. Remodelling sites where identified: elements were removed or added respectively where strains are under 100 με or exceed 3000 με. Strain distribution in bone sample is due to a structure effect, but also a material heterogeneities distribution.

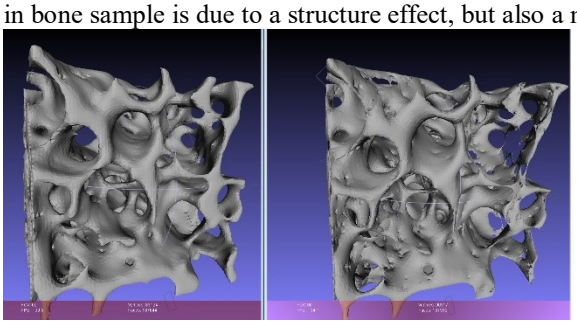
Figure 1: Degradation of cancellous bone from initial to remodelled (after 5 year)

4 Conclusions

Geometrical bone degradation was simulated and overall stiffness of the sample was computed. The developed model took into account the hypermineralization of bone tissue. As alendronate treatment increased bone mineral density, but also degree of mineralization of bone, this model can simulate medical treatment on bone stiffness, and quantify fracture risk in particular in osteoporosis case.

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