Motivation

Investigation of micro- and nanomechanical characteristics of HYDROXYAPATITE GRANULES for regenerative medicine

Porous hydroxyapatite (HA) globules [1] have proven as a successful tissue engineering strategy to handle bone defects in vivo, as was shown in studies on human mandibles (see Figure 1). These granules need to provide enough porous space for bone ingrowth, while maintaining sufficient mechanical competence (stiffness and strength), in this highly load-bearing organ. This double challenge motivates to scrutinize deeper into the micro- and nanomechanical characteristics of such globules, as to identify possible optimization routes [2].

Methods – µCT, polycrystal micromechanics, Finite Element Analysis

Micro CT imaging
SKYSCAN 1172 micro computed tomography (µCT)
Stack of 583 8-bit grey-scaled images, each consisting of 748x748 pixels

Image processing

- Segmentation
- Thresholding
- Decrease number of voxels: merging algorithm
- Translation of voxels into cubic Abaqus finite elements

Result

Porosity

Translate the finite element specific porosities to finite element specific elastic properties

Finite Element Analysis

Uniaxial compression test:
- Forces at the poles by prescribed displacement of 0.1% of the globule’s diameter “BC1” (physiologic strain)
- Fixed displacements perpendicular to the loading direction “BC2”
- Zero displacement at “BC3”

Aim: decipher the mechanical behavior of the globule; through comparison of three differently precise models:
1) Finite Element model with voxel-specific elastic properties
2) Finite Element model with homogeneous elastic properties of solid voxels, related to the average nanoporosity
3) Analytical sphere model of Lurje [7], considering nano- and micropores, but no cracks

Results

Voxel-specific elasticity

Probability density functions of the finite element-specific elastic material properties, namely Young’s modulus and Poisson’s ratio, over all finite elements:

Maximum principal stresses

Results of Finite Element simulation, with element-specific heterogeneous (a)—(c) and homogeneous (d)—(f) elastic properties: maximum principal stresses in three perpendicular cross-sections through the center of the globule. The cross-sections are parallel to the y-z (g), x-z (h) and x-y (i) planes. Abscissa: voxel phase fraction; ordinate: ratio of all values lies between 0—100% (see color legend (j))

Effect of heterogeneity and cracks

Neglect of heterogeneity of nanopores (and corresponding voxel-specific elastic properties) leads to a stiffness overestimation of about 5% (comparison of pore forces in models 1 and 2), while the neglect of crack morphology results in a stiffness overestimation by a factor of around 80 (comparison of pore forces in models 1, 2, and 3).

Outlook

Currently, we extend this type of analysis to strength properties [5], providing a path finally leading to fully patient-specific analysis of organ-biomaterial compounds in regenerative orthopedics and dentistry.

References: