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CT-BASED MULTISCALE ELASTICITY OF HYDROXYAPATITE GRANULES FOR REGENERATIVE MEDICINE

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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].

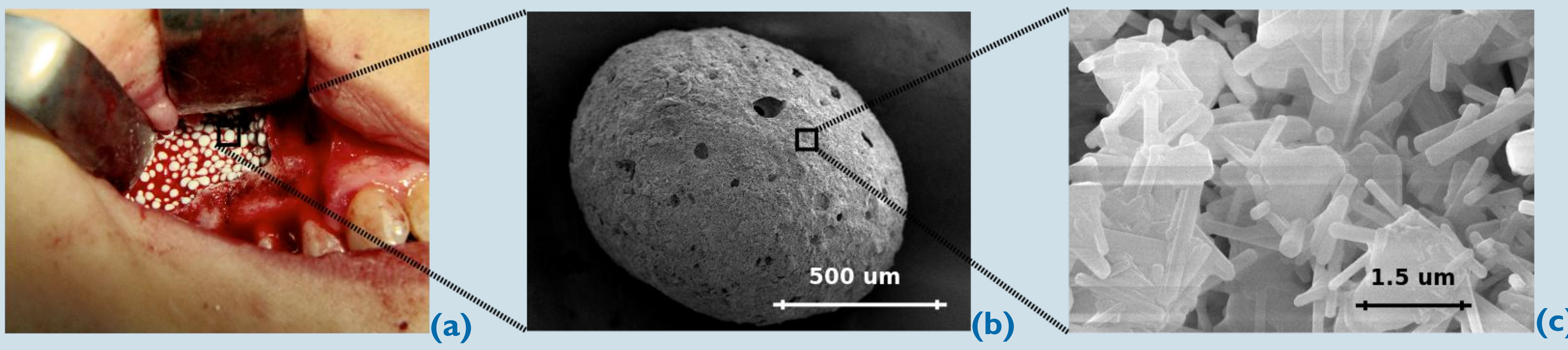
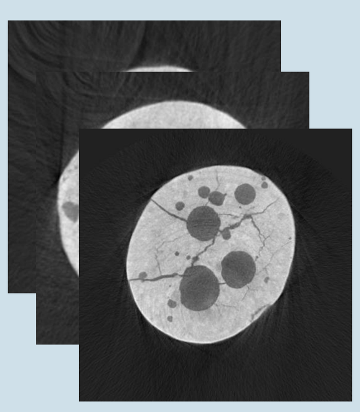


Fig. 1: (a) Hydroxyapatite granules used in oral surgery as bone-filling material; (b) Scanning electron micrograph (SEM) image of the porous globule; (c) SEM image showing nanoporous polycrystals building up the granule

Methods – μCT, polycrystal micromechanics, Finite Element Analysis

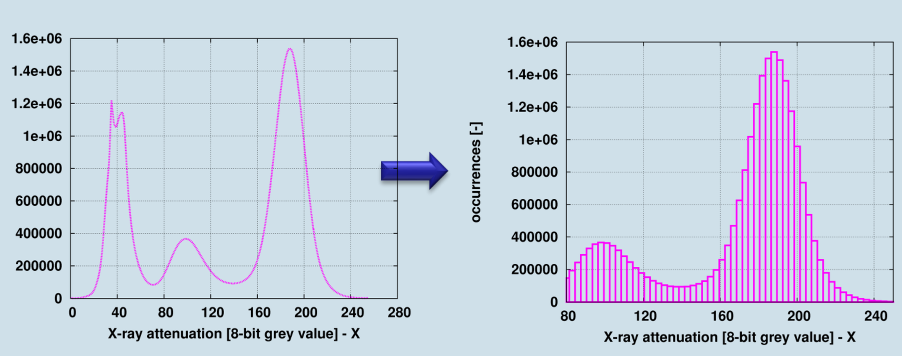
Micro CT imaging



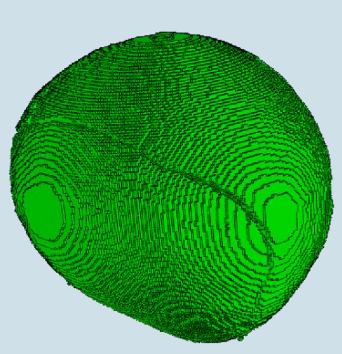
SKYSCAN 1172 micro computed tomography (μCT)

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



SIMULIA Abaqus Finite Elements model of globule

Attenuation-to-nanoporosity conversion

Considering the average rule for X-ray attenuation coefficients of composite materials [3, 4], which in our case read as:

$$X = X_{HA}(1-\phi_{nano}) + X_{air}\phi_{nano}$$

we derive the voxel-specific nanoporosity from voxel-specific grey values:

$$\phi_{nano}(X) = \frac{X - X_{HA}}{X_{air} - X_{HA}}$$

ϕ_{nano} ... voxel-specific nanoporosity
X_{HA} ... attenuation of a voxel entirely filled with hydroxyapatite
X_{air} ... attenuation of a voxel entirely filled with air
$p(x)$ ... probability density function of X

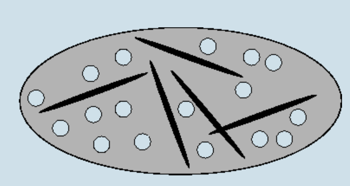
X_{HA} follows from the *total* micro-and nanoporosity of the globule, ϕ_{total}, which is accessible from mass and volume measurements:

$$X_{HA} = \frac{1}{1-\phi_{total}}\left\{X_{air}(\phi_{micro} - \phi_{total}) + \int_{X_{thr}}^{255} p(X)dX\right\}$$

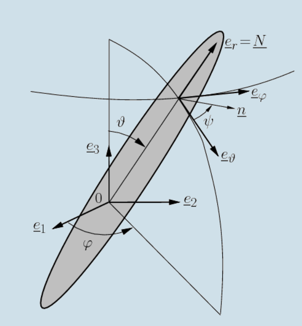
No phantom calibration necessary !

Nanoporosity-to-elasticity conversion

Continuum micromechanics representation:

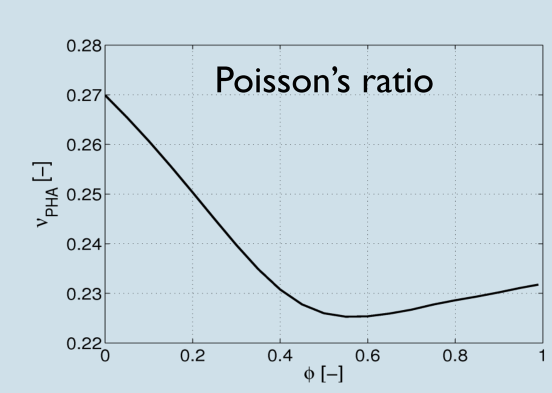


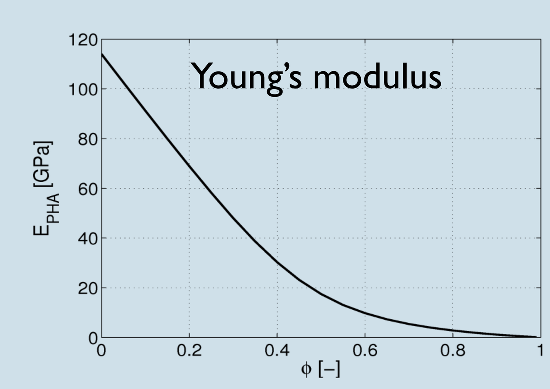
Porous polycrystals built up by HA crystals oriented in all space directions [5].



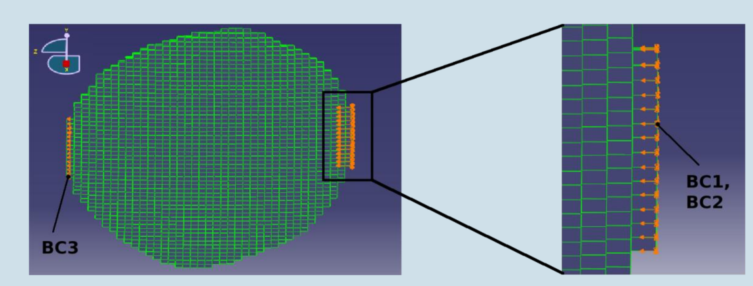
Model input:
- Hydroxyapatite stiffness [6] (bulk modulus 83 GPa, shear modulus 45 GPa)
- Nanoporosity

Translation of finite element-specific nanoporosities 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"

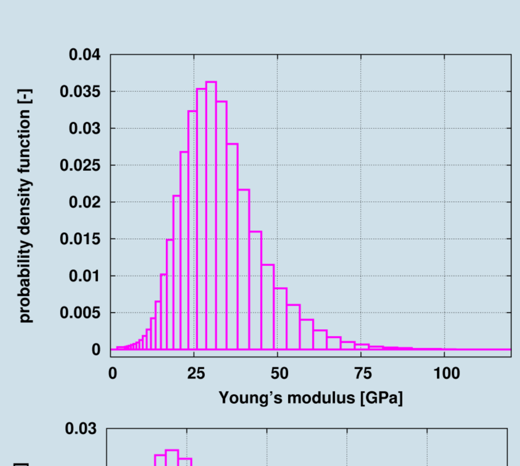
(Realized in SIMULIA Abaqus v6.7-2)

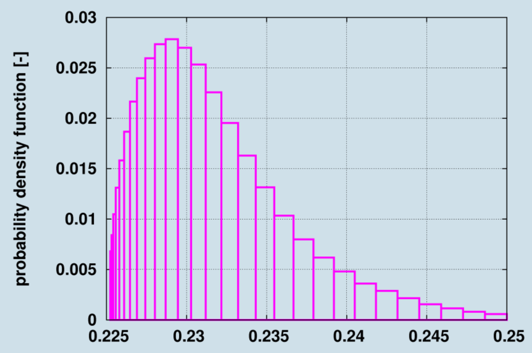
Aim: decipher the mechanical behavior of the globule; through comparison of three differently precise models:
1) Finite Element model with voxel-specific elastic properties
2) Finite Element model with homogeneous elastic properties of solid voxels, related to the average nanoporosity
3) Analytical sphere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

Results

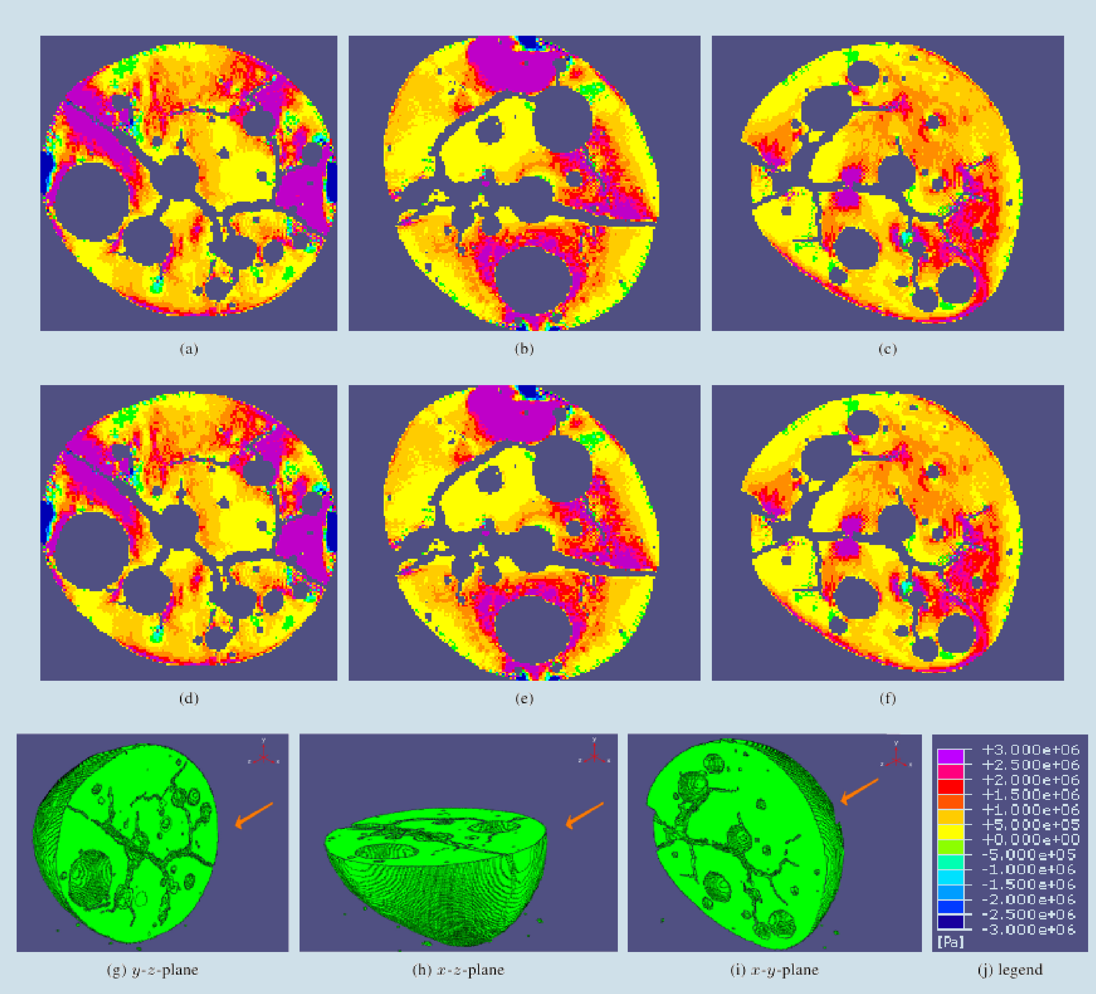
Voxel-specific elasticity

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. About 95.9% of all values lie between +/- 3MPa [see color legend (j)].

Effect of heterogeneity and cracks

Neglection of heterogeneity of nanopores (and corresponding voxel-specific elastic properties) leads to a stiffness overestimation of about 5% [comparison of pole forces in models 1) and 2)]; while the neglection of crack morphology results in a stiffness overestimation by a factor of around 80 [comparison of pole 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.

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