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On the Influence of Cancellous Bone Structure upon the Electric Field Distribution of Electrostimulative Implants

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Motivation

- At the University of Rostock, an electrostimulative total hip revision system is being developed to support the regeneration of bone tissues as described by Basset et al. [1].

- In previous works the macroscopic electric field distribution has been investigated using a layered bone model consisting of cortical and cancellous bone.

- However, cancellous bone forms a spongy or trabecular structure which aligns along the main stress directions.

- In the present work, the behavior of the electric field within this microstructure is being investigated.

Fig. 1: Prototype of an electrostimulative acetabular cup

Preparation of the µCT sample for COMSOL

- In previous works, bone samples have been taken from the femoral head and mapped using micro computer tomography (µCT) [2].

  - Height: 13 mm
  - Diameter: 12 mm
  - Voxel edge size: 26 µm

  ⇒500 slices with 475 x 475 pixel
  ⇒112.8 million voxels

- At each data point the absorption of the x-ray correlates with the density of the material (Fig. 2, Tab. 1).

- The absorption is represented by a 16-bit unsigned integer number (brightness value).

- Using MATLAB®, the edges have been minimized and data points were saved to a ASCII text file using the grid data format.

  - File size: 638 MB

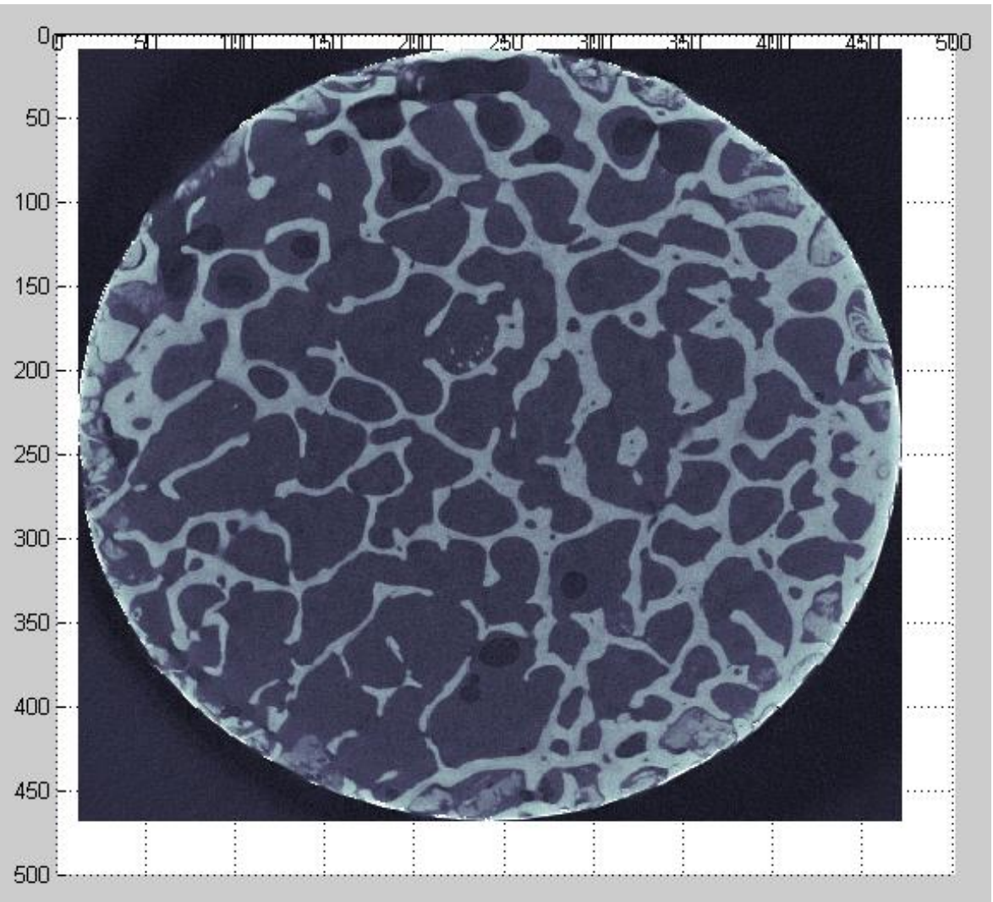

Fig. 2: Matlab illustration of one slice of the µCT after reduction of the edges

Material	Content
Water	10 % - 25 %
Inorganic materials (Mostly hydroxyapatite)	45 % - 55 %
Organic materials (Mostly Collagen I)	Rest

Tab. 1: Material contents in cancellous bone [3]

Definition of the COMSOL model

- Using COMSOL Multiphysics® 4.4 the electric currents interface has been used to conduct a stationary study.

- **Geometry**: Cylinder (smaller cylinder to avoid disturbances due to the drilling)

  - Height: 13 mm (11 mm)
  - Diameter: 12 mm (11 mm)

- **Material**: Mathematical equation including the locally changing brightness value from the previously generated text file.

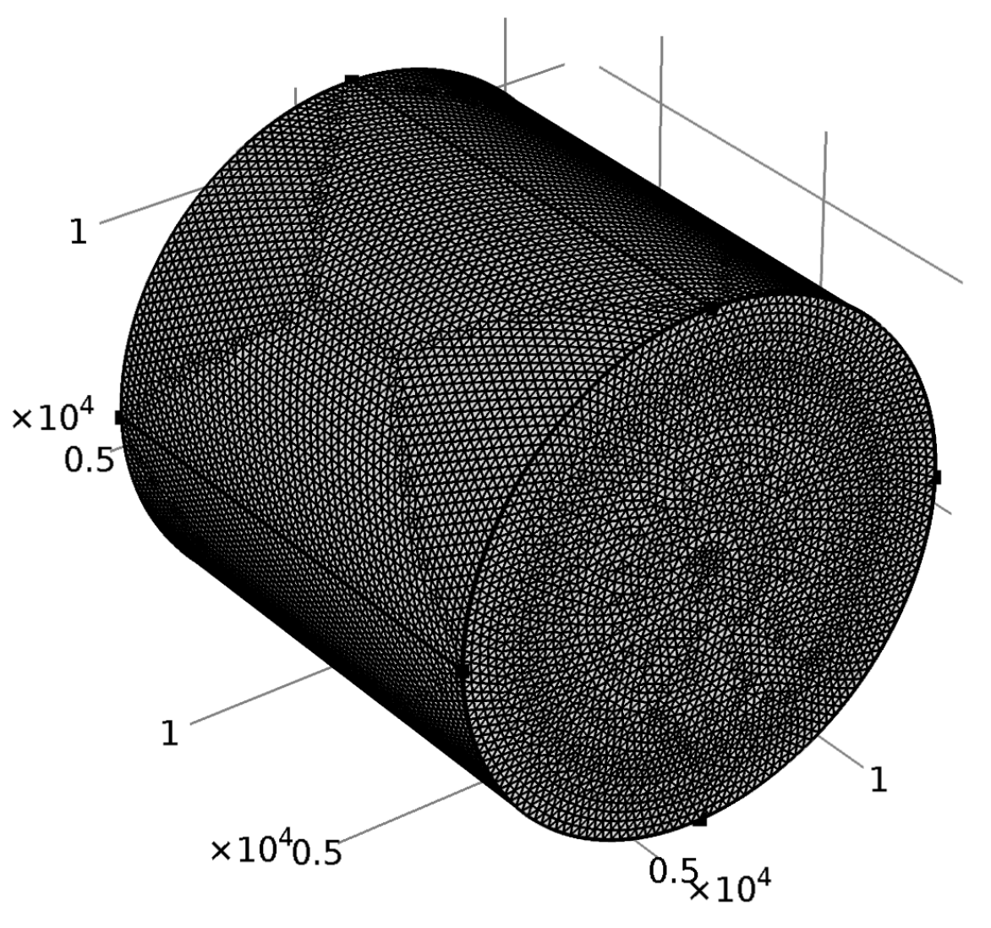

Fig 3: Predefined "extremely fine" tetrahedral mesh: 1,699,959 mesh cells

- **Sources**: Terminals at the upper and lower boundary of the cylinder providing an overall voltage of: 0.91 V (0.77 V)

⇒These sources provide a constant electric field of 70 V/m within a homogeneous tissue.

- **Mesh**: customized tetrahedral mesh resulting from a convergence analysis

- **Solver**: GMRES-Solver with ILU-Preconditioner

Basic idea

- Each brightness value represents a certain mixture of different bone tissues with a certain electrical conductivity.

- The goal of this study is to correlate each brightness value with a conductivity basing on values from literature (Fig. 4).

- Brightness values above 25000 are supposed to be pure hydroxyapatite with a conductivity of 0.

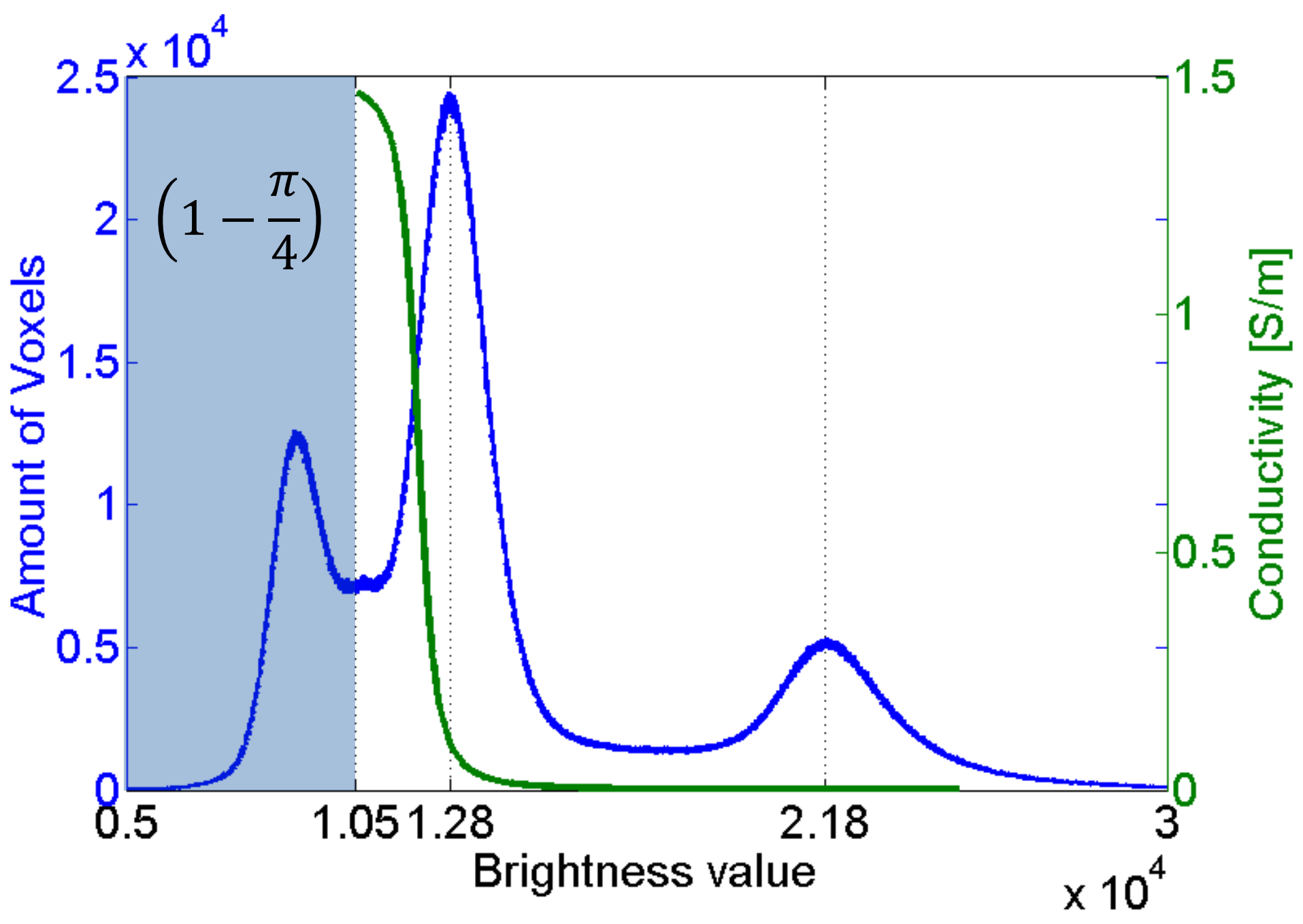

Fig. 4: Amount of voxels with a certain brightness value (blue) and correlation with the conductivity using a sigmoidal approach (green)

- Brightness values below 10527 are supposed to include the voxels in the corners of Fig. 2 (1-п/4 of all voxels). For this reason they are neglected.

- Different approaches are used to correlate the locally changing Brightness value $B(x,y,z)$ with the electrical conductivity $\sigma(x,y,z)$, where α and β are parameters to reach certain conductivities from literature:

  - Linear approach: $\sigma(x,y,z) = -\alpha \cdot B(x,y,z) + \beta$

  - Exponential approach: $\sigma(x,y,z) = 0.002 \cdot 10^{\alpha\cdot(-\frac{B(x,y,z)}{\beta}+1)}$

  - Sigmoidal approach (Fig. 4): $\sigma(x,y,z) = 0.75 \cdot \left(-\frac{B(x,y,z)-\beta}{\sqrt{\alpha+(B(x,y,z)-\beta)^2}}+1\right)$

Results

- Using the parametric sweep α and β are investigated to match certain values from literature:

  - Collagen I at a brightness value of 12800.
  - Cancellous bone for the whole sample.

- The steeper the slope of the correlation graph for the conductivity, the bigger the deviations from the expectancy value of the electric field (Compare Fig. 6 with Fig. 7).

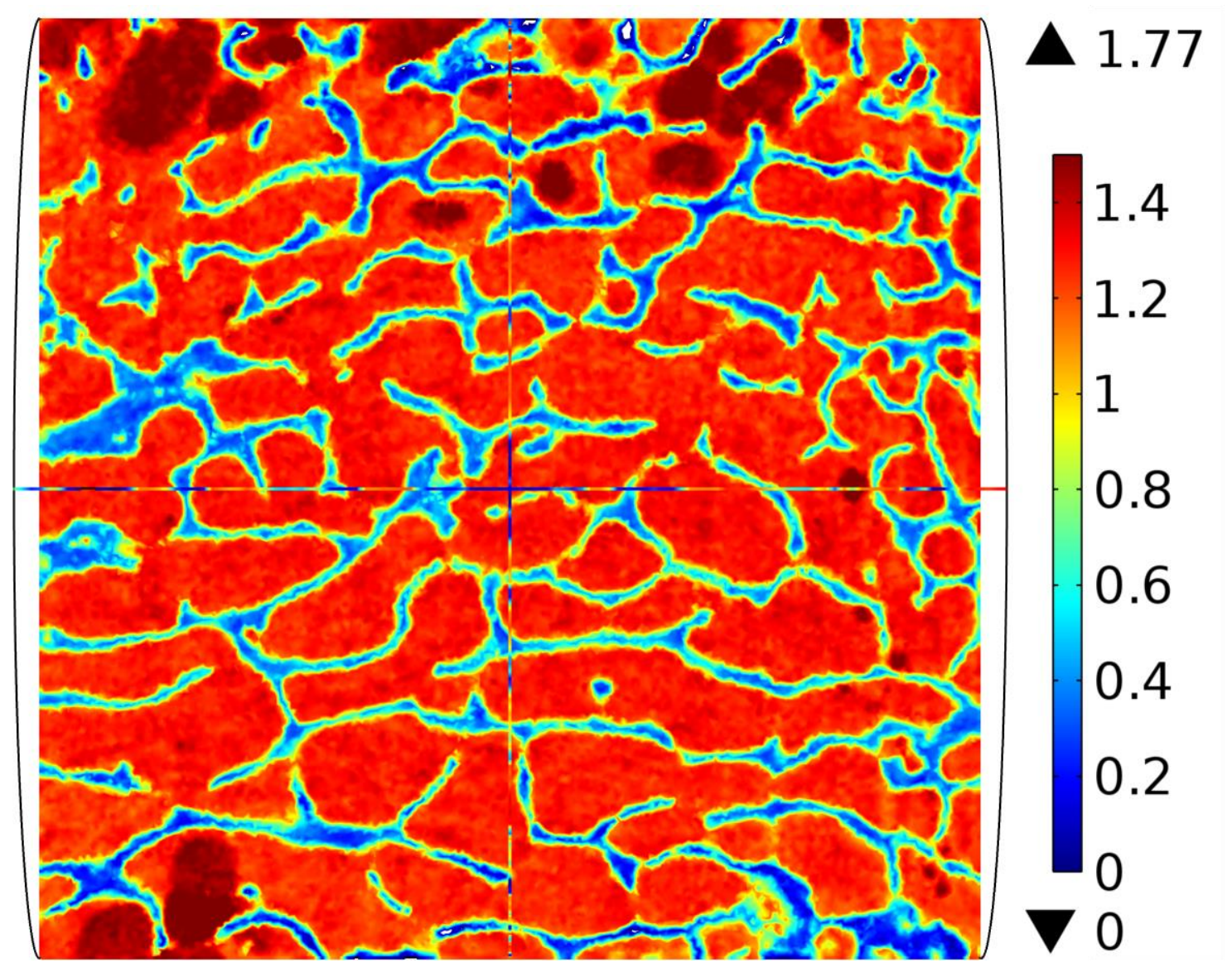

Fig. 5: Conductivity distribution [S/m] within the sample using the linear approach without consideration of conductivity values from literature

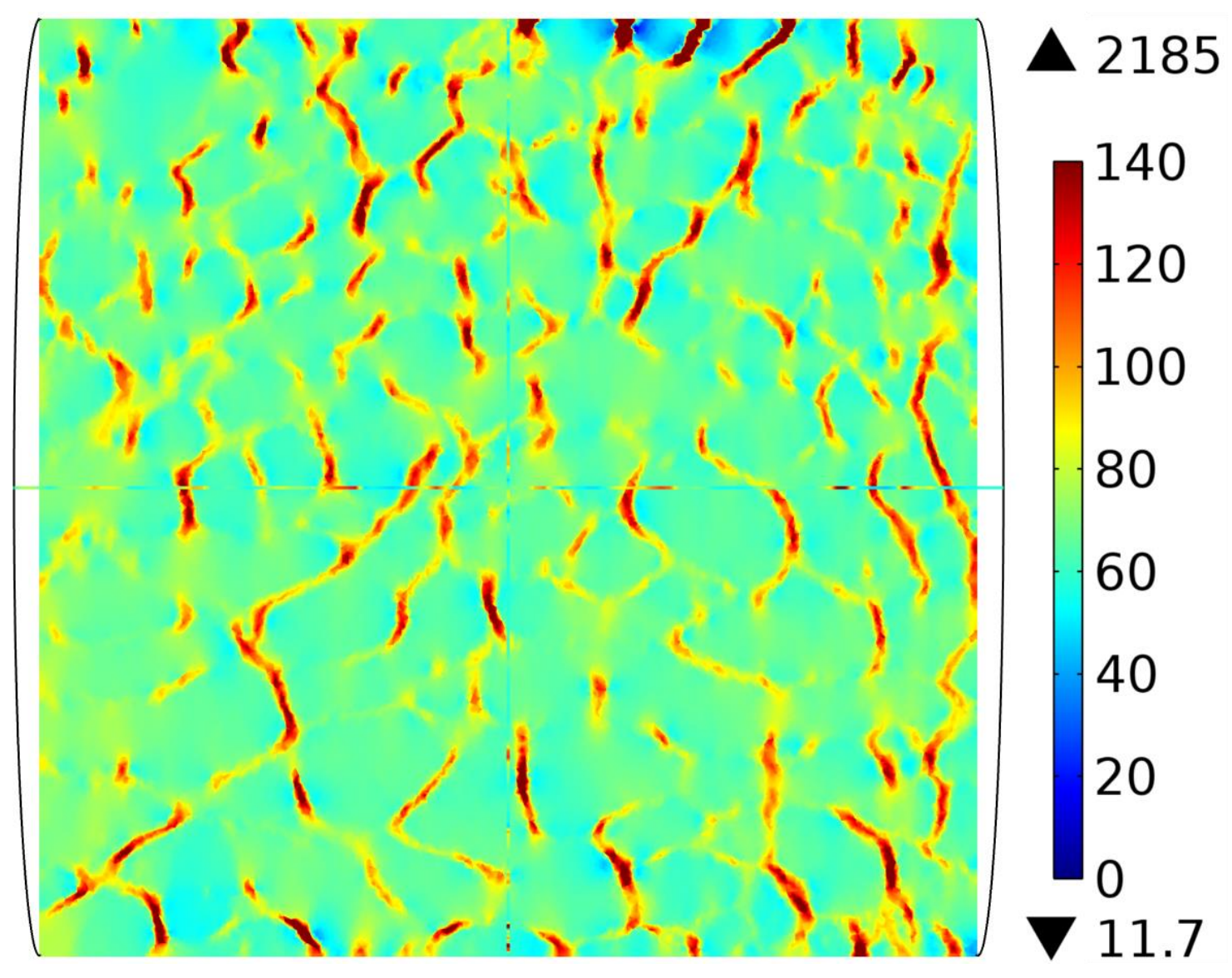

Fig. 6: Electric field distribution [V/m] according to Fig. 5: 70 V/m (green) is the expectancy value

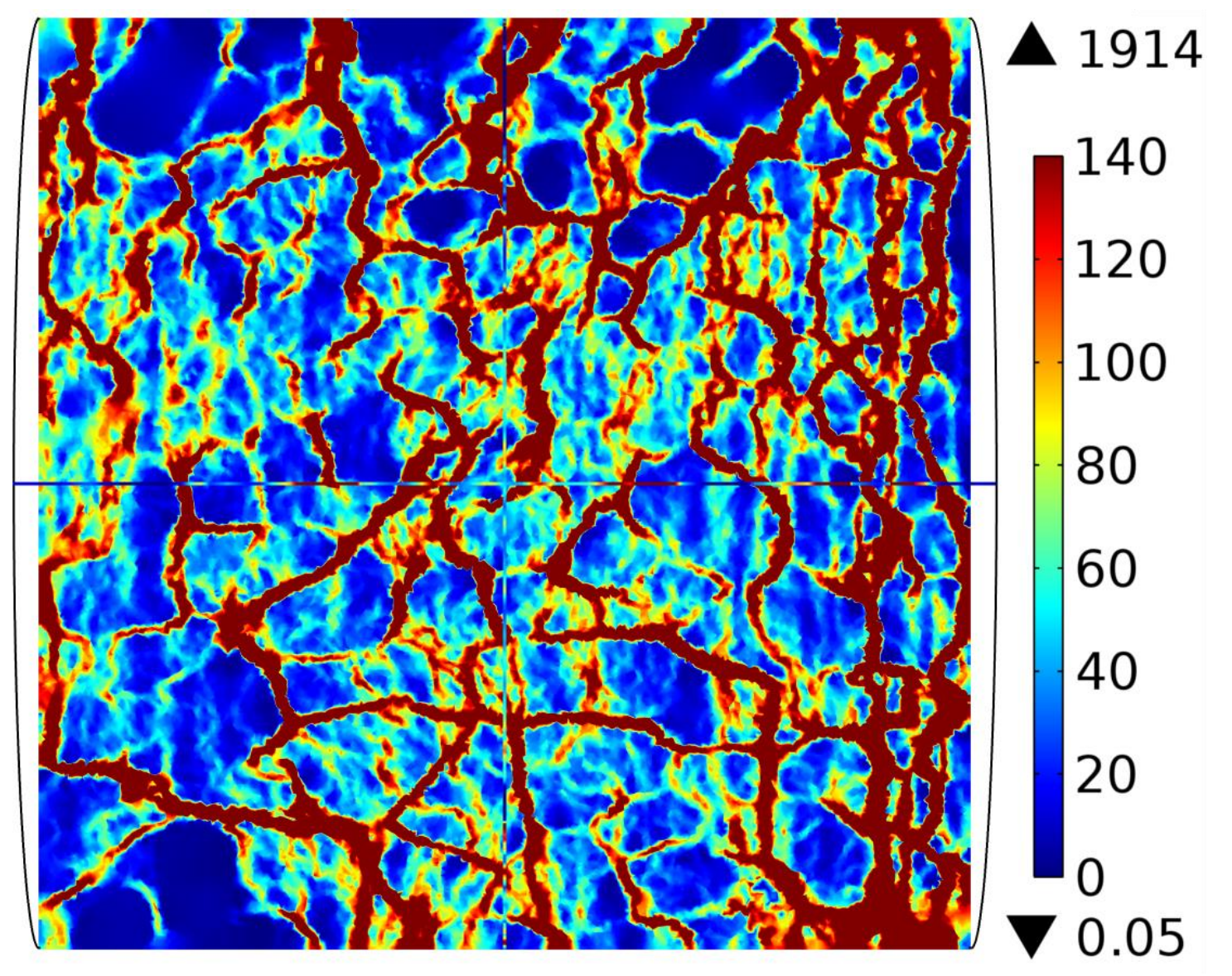

Fig. 7: Electric field distribution [V/m] within the sample using the sigmoidal approach considering literature values for collagen I as well as for cancellous bone averaging over the whole sample

Acknowledgement

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Reverences:
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