Investigation of the Electric Field Distribution within an Electro-stimulated Microstructure of Cancellous Bone*

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Electrostimulative fields are used to accelerate bone regeneration after fractures and to treat bone diseases. Most of these systems have upper and lower thresholds for electromagnetic fields, which have proven to have a positive effect towards bone growth. The biomechanical background, however, is still subject of ongoing research. Using numerical simulation, this paper investigates the field distribution within the microstructure of cancellous bone, which is often regarded as a homogenous structure. Basing on microscopic computer tomography (µCT) a small sample of cancellous bone is separated in cortical bone and red bone marrow. In order to achieve an efficient, automatable procedure this is based on the absorption values of the µCT. The field distributions, which result from a specially implemented voltage source, suggest that bone generating cells are exposed to higher electric fields than expected.

***Index Terms*—Electrical Stimulation, Implantable Biomedical Devices, Bioimpedance, Numerical Simulation, Optimization**

I. Introduction

THE DISCOVERY by Bassett et al. [1] that electromagnetic fields have an accelerating effect on bone growth and regeneration resulted in a multitude of surgical and orthopedic applications [2]. This effect is now being implemented in an electrostimulative total hip revision system at the University of Rostock [3]. This system uses inductively coupled electrodes to cause an electric field oscillating with 20 Hz and with a field strength between 5 – 70 Vm^{-1} in close proximity to the implant as well as within targeted damaged regions of the bone.

The numerical models of pelvic and femoral bone are based on computer tomography (CT) scans of patients. Typically, they are only segmented into three domains: the cortical bone, which forms the hard outer shell, the cancellous bone, which is the primary target of bone stimulation and – in case of the femoral bone – the medullary cavity, which is filled with bone marrow. All those tissues are defined as homogenous materials with electrical properties taken from the literature [4]. Cancellous bone, however, is not a homogenous material but a porous structure comprising soft bone marrow [5]. In this study, the effects of the microstructure are investigated numerically within a small sample of cancellous bone. The necessary structural data is taken from a microscopic computer tomography (µCT) scan and correlated with the material properties from the literature [4], using different methods of correlation. The simulated electric fields are compared to the field facilitated by a homogenous medium.

II. Methods

A. Preparation of the µCT

The idea behind this study is to use the µCT scans directly as input values for the numerical model, skipping the segmentation step. The original scan has been done for a cylindrical sample (height: 13 mm, diameter: 12 mm) of cancellous bone taken with a hole saw from a human femoral head at the University Orthopedic Clinic of Rostock [6]. The sawing process abraded the edges as it can be seen in Fig. 1. The µCT (Phoenix Nanotom, X-ray, Nanofocus, GE, Wunstorf, Germany) resolved the sample in a Cartesian grid with 475 x 475 x 500 voxels. The edge length of each cubic voxel is 26 µm. Like conventional x-ray radiographies, the µCT data only comprises information about x-ray absorption, which correlates with the tissue density. In the raw data format this absorption is defined for every voxel as an unsigned integer value between 0 and 65,535. This value grows with the tissue density, which means that cortical bone has an absorption value around 21,800, while the absorption value of bone marrow is around 12,800.

These values are taken from the histological analysis of the complete bone sample as shown in Fig. 1. Here, the total amount of voxels for each absorption value τ is depictured showing three Gaussian curves. Each of these curves represents one material as well as transitions between these materials within one voxel and measuring inaccuracies of the µCT. Since the cylindrical sample has been measured within a rectangular-shaped environment, the first 10,527 absorption values can be considered as air, as it can be seen as black corners of the µCT slice shown in the upper right of Fig. 1. Around τ = 12,800 a soft tissue (bone marrow) is defined, which includes the grey areas within Fig. 1, while the light grey and white values are considered to be a hard tissue (cortical bone).

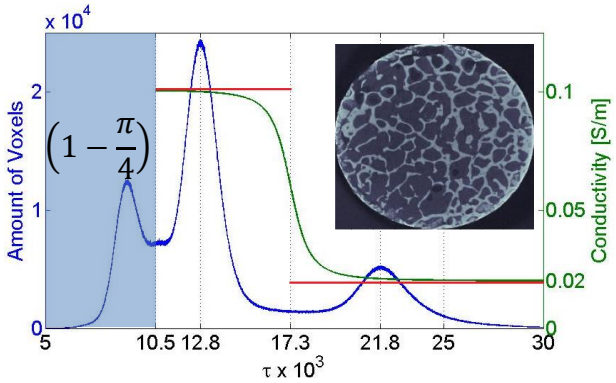

Fig. 1. Histogram of the amount of voxels for every absorption value (blue) and the correlated conductivity using a step function (red) and using a sigmoidal approach (green).

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B. Model setup

The numerical simulations have been conducted using the electric currents module of the FEM software COMSOL Multiphysics® 5.0. Since the µCT data is not segmented, the computational domain is defined as a cylinder with a diameter and height of 11 mm. By cutting away the boundaries of the larger cylinder within the numerical model, the abraded edges (see Fig. 1) are neglected. By applying a voltage of 0.77 V between the top- and bottom-boundary of the domain, a homogenous medium would facilitate a constant electric field of 70 Vm^{-1}. In this work, however, the conductivity of the medium is defined at every point of the domain by the absorption value $\tau(x,y,z)$, using one of these correlations:

$$\sigma = 0.02 + 0.081 \cdot (\tau(x,y,z) < 17300) \ [Sm^{-1}] \quad (1)$$

$$\sigma = 0.02 + 0.0405 \cdot \left(1 - \frac{\tau(x,y,z)-17300}{\sqrt{\alpha+(\tau(x,y,z)-17300)^2}}\right) \ [Sm^{-1}] \quad (2)$$

Equation (1) considers the conductivity as a step function, which is defined using a Boolean expression. The conductivities are set to 0.101 Sm^{-1} and 0.02 Sm^{-1} within the soft (red bone marrow) and hard tissue (cortical bone), respectively [4]. The threshold is set to 17,300, which is the average absorption value between the two Gaussian peaks in Fig. 1. Using this equation, transitions between soft and hard tissue are completely neglected and each voxel is assigned to one discrete tissue. To get a smooth transition between both tissues eq. (2) is used to establish a sigmoidal approach, where the conductivity of the absorption value 17,300 is exactly in-between both conductivity values from the literature. The variable α is used to vary the slope of the sigmoid function. This way, it can be used to adjust the conductivity of the whole sample to agree with the literature value for cancellous bone [4].

III. Results and Discussion

Figure 2 shows the electric field distribution for the step approach (2a) as well as the absolute difference between the step approach and the sigmoidal approach (2b). As it can be seen in Fig. 2a, especially within the cortical bone substantially higher electric fields (red) than the anticipated 70 Vm^{-1} (green) can be expected. Within the practical implementation of the electrostimulative system, electric fields above 70 Vm^{-1} are considered to be overstimulation, which is assumed to have a negative effect on bone cells. However, most of the bone generating cells can be found attached to the cortical bone structure [5]. Since until today the microstructure of cancellous bone has been neglected during the electrode design [7], the results of this simulation lead to the conclusion that either the area of overstimulation has to be redefined for the design of bone stimulation systems or that the upper limit for cellular stimulation is substantially above 70 Vm^{-1}.

Even under consideration of smooth transitions between the conductivity of bone marrow and the conductivity of cortical bone, as implemented by equation (2), nearly the same field distribution occurs. Figure 2b shows the absolute difference between the two field distributions, introduced in this short

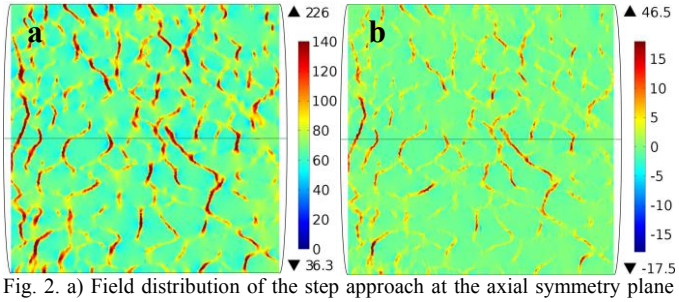

Fig. 2. a) Field distribution of the step approach at the axial symmetry plane XoZ. b) Difference between the field distribution of step approach and the field distribution of the sigmoidal approach at the symmetry plane XoZ.

paper. Of course, especially at the boundaries between marrow and cortical bone this difference is the highest due to the continuity condition for the electric current density. Higher differences between the conductivity of two materials lead to higher differences between the electric fields at this boundary. The smoother the transition is, the smaller are those field deviations. Smooth transitions are characterized by the slope of the sigmoidal function as defined by the variable α in (2).

The variable α has particularly been selected with regard to a parameter sweep to reach a conductivity of 0.0789 Sm^{-1} for the whole bone sample. This is the conductivity of cancellous bone as defined by Gabriel et al. [4]. During this parameter sweep, it became obvious, that the general conductivity already is close to this value. For the step function model as defined by equation (1) a conductivity of 0.0769 Sm^{-1} has been derived. Since this value only refers to one µCT scan of cancellous bone, a conclusion about the validity of this step approach cannot be made. The full paper will investigate the conductivities within several µCT-bone samples including different resolutions to verify this finding. In addition, a second material property will be investigated basing on the approaches used in this paper. During numerical simulations the dielectric properties of bone have proven to be insignificant due to the low stimulation frequency of 20 Hz. However, these findings were made neglecting the bone microstructure which will be investigated in the full paper.

IV. References

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