Numerical Simulation of the Functional Electromagnetic Stimulation of the Human Femoral Bone using COMSOL

Y. Haba*[1], W. Kröger[2], H. Ewald[2], R. Souffrant[1], E. Otterstein[3], W. Mittelmeier[1] and R. Bader[1]
[1]Department of Orthopaedics, University of Rostock, Biomechanics and Implant Technology Research Laboratory
[2]Institute of General Electrical Engineering, University of Rostock
[3]Institute of Physics, University of Rostock
*Doberaner Strasse 142, D-18057 Rostock, Germany, yvonne.haba@med.uni-rostock.de

Abstract:

C. Gabriel and S. Gabriel [1, 2, 3] identified the conductivities of human bone cancellous with human autopsy materials. In the present study we determined the relative conductivities and permittivities of fresh cortical and cancellous bone of human femoral heads in slices of 1 mm thickness. The identified conductivities of human trabecular bone were used for the electromagnetic field simulation by means of COMSOL using a model reconstructed from micro-computed tomography (Micro-CT) data. The calculated model consists of the bone geometry surrounded by a blood filled cylinder and is defined with three different trabecular electric material parameters. The COMSOL simulation shows the congruence between our measured electric bone material parameters and the parameters published by Gabriel et al. [1, 2, 3]. These calculations were done with specific relation to the bipolar induction screw system for electromagnetic stimulation of human femoral bone.

Keywords: Human femoral bone, Electric field simulation, Electromagnetic stimulation, Micro-CT

1. Introduction

The electromagnetic stimulation is being used worldwide and leads to regeneration of bone and other tissue types. For example, the bipolar induction screw system (BISS) [4] is an electromagnetic implant system developed for recalcification and remineralization of bone defects in osteonecrosis and fracture healing. A primary coil placed around the patients hip induces current into a secondary coil which is integrated in the BISS implant (figure 1). It consists of a coil and a tip, which is electrically isolated from the screw shaft. The induced current creates an electromagnetic field between tip and shaft and in the surrounding tissue. However, the optimum parameters of the bone electrostimulation were mainly determined by clinical experience so far [5].

The calculation of electromagnetic fields for bone regeneration is based on the knowledge of the electromagnetic potentials in the bone. Gabriel et al. [1, 2, 3] identified the conductivities of human cancellous bone with human autopsy materials. These values were used for calculations of electromagnetic fields in the human body.

Contrary to Gabriel et al., we present data gained from fresh human bone material immediately after femoral head resection during total hip arthroplasties.

The identified electromagnetic parameters were used in numerical simulations of a reconstructed bone structure based on a Micro-CT-scan. The calculation of small bone samples is a preliminary work in order to establish a numerical model for the simulation of electromagnetic implants in the surrounding bone stock.

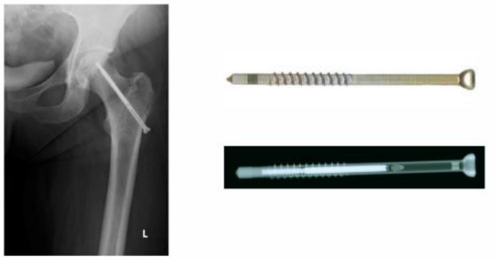

Figure 1. Clinical application of the bipolar induction screw system (BISS) at the femoral head (left). Illustrations and X-Ray of the BISS implant system showing the integrated internal secondary coil (right).

2. Materials and Methods

MEASUREMENT OF IMPEDANCE IN DIFFERENT BONE LAYERS

For the measurements of impedance in bone, we used three femoral heads, two female (48 and 77 years old) and one male (68 years old).

Each femoral head was mounted in a clamp device and cut down in slices of 1 mm thickness using a microtome (Jung AG, Heidelberg, Germany).

After each cut was made, the impedance of the bone was measured with a 7600 Plus Precision LCR-meter (QuadTech, Maynard, MA, USA) with the Four-Point Method in the remaining bone sample. A voltage of 5 V with a frequency of 20 Hz was used as feeding current in the four point method measurements.

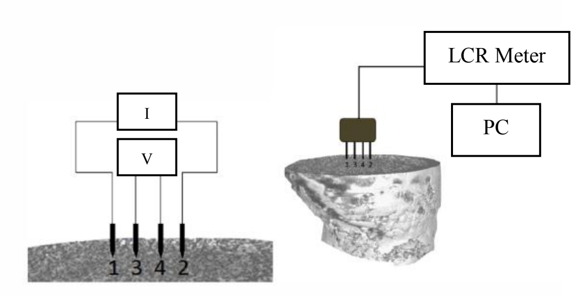

Figure 2. Schematic of the four point method.

The measured impedance, calculated relative conductivity and permittivity was averaged between the three femoral heads for each layer.

ANALYSIS OF ELECTRICAL POTENTIAL IN A MICRO-CT BONE SAMPLE

The femoral head of the male donor was used for generation of a Micro-CT-scan, figure 3. We used a Micro-CT (Nanotom Phoenix, X-ray, Nanofocus, GE, Wunstorf, Germany).

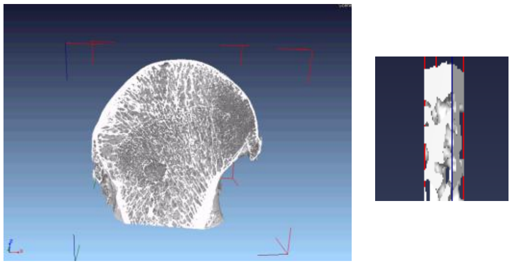

Figure 3. Micro-CT of human femoral head (left) and a cut of the femoral head centre (right).

The used detector had a resolution of 2284x2284 pixels, resulting in a voxel size of 29.5 µm. Figure 3 shows a cut of the femoral head centre. This cut had a size of 1.6x1.6x3 mm and was used for further analysis. The bone sample was three-dimensionally reconstructed from the Micro-CT-data using the Software AMIRA 4.1 (Mercury computer systems Inc., MA, USA).

The data received from the segmentation in AMIRA was exported for further handling into a STL (surface tessellation language) file. This file contains the position of the segmentated point clouds (landmarks) and describes the triangulated, unstructured surface geometry of a three dimensional object. The triangles are defined by three edge points and the surface normal for defining the interior and exterior surface.

The STL file was imported into COMSOL Multiphysics (COMSOL Multiphysics GmbH, Göttingen, Germany, version 3.5a) using the integrated CAD import module. The bone model is centered in a cylinder with a length of 4 mm and a diameter of 12.5 mm.

Numerical simulations of the electric currents were performed as time harmonic quasi-static, with the AC/DC Module of COMSOL.

Three subdomains for three different bone layers and one subdomain for the blood filled cylinder were used (figure 4). The measured conductivities at the human femoral head slices from cortical bone (layer 1 and 2) to cancellous bone (layer 3) were applied in the electromagnetic field simulation (case 1).

In a second scenario (case 2) were used for the numerical simulation two subdomains for two different bone layers and one subdomain for the blood filled cylinder (figure 5) using the electrical material parameters published by Gabriel et al. [1, 2, 3] (table 1) .

Table 1: Material parameters according to Gabriel et al. [1, 2, 3]

Material	**Conductivity**	**relative Permittivity**
	σ [S/m]	**ε_r**
Human Blood	0.7	5’260
Cortical bone	0.020045	25’119
Cancellous bone	0.078902	4’020’200

The shell of the cylinder is defined as electric insulation, while an electric potential difference of 700 mV was applied between top and bottom surface of the cylinder. The different defined bone layers are set to continuity.

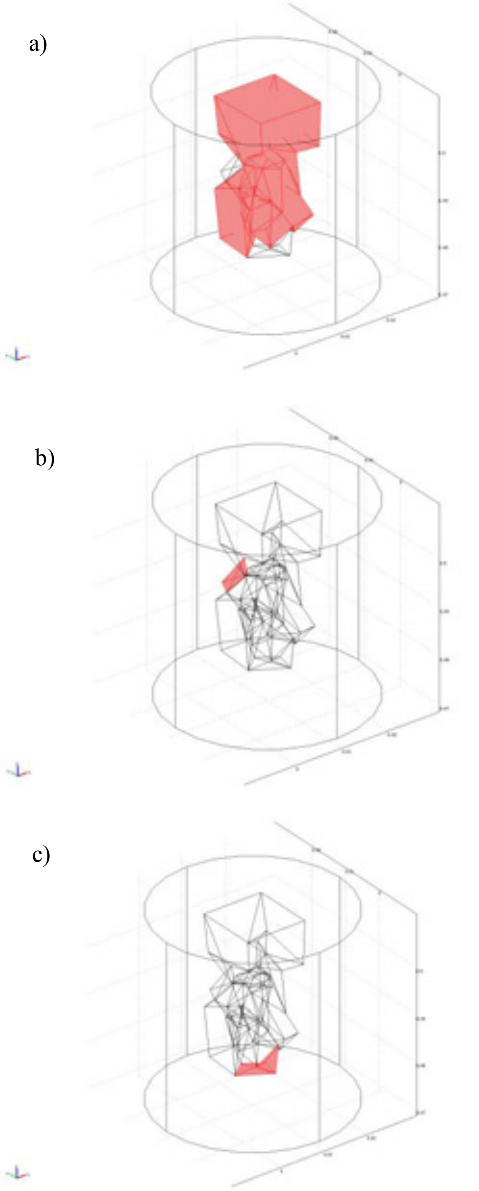

Figure 4. Subdomain settings of cortical bone layer 1 (a) & 2 (b) and cancellous bone layer 3 (c).

The linear system was solving using the UMFPACK direct solver. Electric potential and the current density in the human trabecular bone model were evaluated and compared between the two cases.

Bone sample and surrounding blood filled cylinder were discretized by approx. 82’000 tetrahedral elements with quadratic approximation function, resulting in 122’000 degrees of freedom.

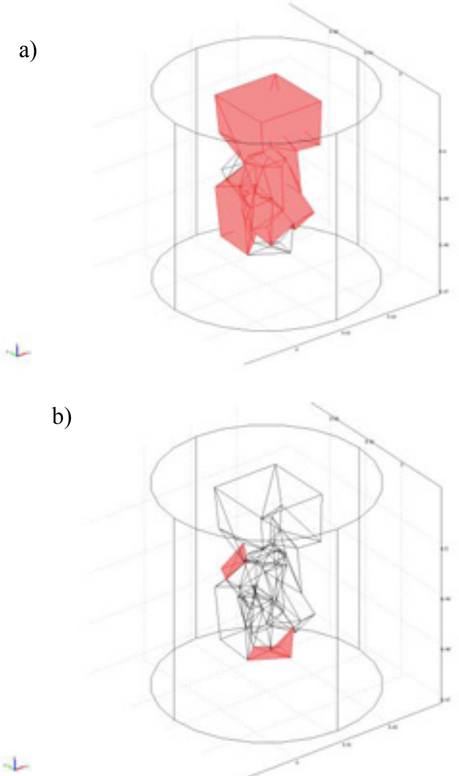

Figure 5. Subdomain settings of cortical bone (a) and of cancellous bone layer 2 (b).

3. Results

MEASUREMENT OF IMPEDANCE IN DIFFERENT BONE LAYERS

The measured conductivity and relative permittivity of human bone is shown in figure 6 and 7. Cartilage was found at level 0, represented by an increase in conductivity compared to cortical bone. Cortical bone was located at layer 1 and 2, while cancellous bone was found in the subsequent bone layers.

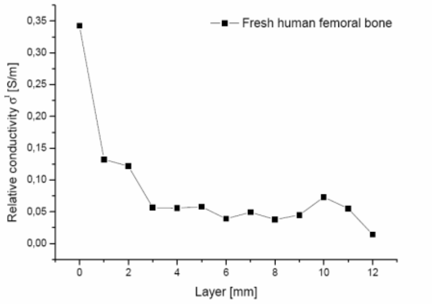

Figure 6. Calculated relative conductivity at the 13 measured layers (Sample: 3).

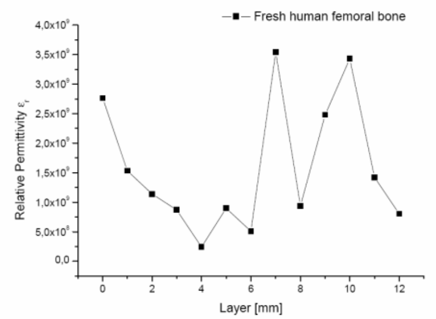

Figure 7. Calculated relative permittivity at the 13 measured layers (Sample: 3).

ANALYSIS OF ELECTRICAL POTENTIAL IN A MICRO-CT BONE SAMPLE

In general, the current density is proportional to the electric field, as expressed by

$$\vec{J} = \sigma \cdot \vec{E}$$

were **J** is the current density, **E** is the electromagnetic field and σ is the electrical conductivity.

The electrical potential distribution from 0V (blue) to 700 mV (red) of the Micro-CT bone sample is shown in figure 8 and 10. The arrows show the direction of the electric field.

The current density plots show the distribution of the current per square meter, comparing the own measured electrical bone material parameter (figure 9) and the parameters of Gabriel et al. [1, 2, 3] (figure 11). The arrows show the direction of the total current densities.

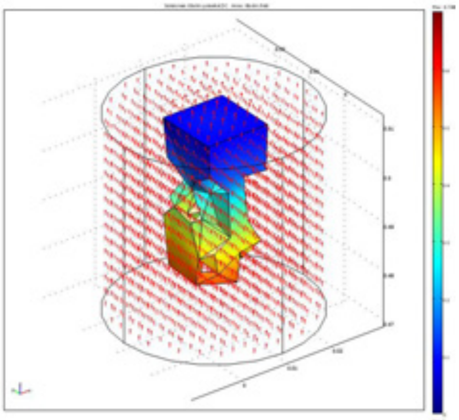

Figure 8. Case 1: The electric potential of 0 V (blue) to 700 mV (red).

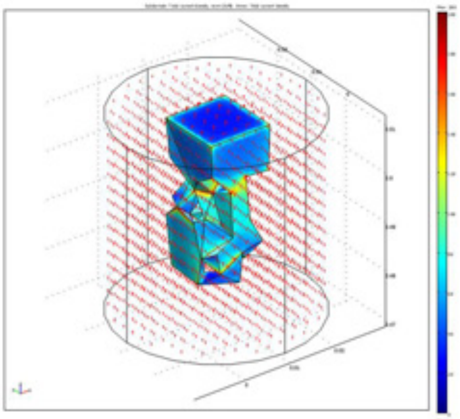

Figure 9. Case 1: The current density of 0 A/m^2 (blue) to 200 A/m^2 (red).

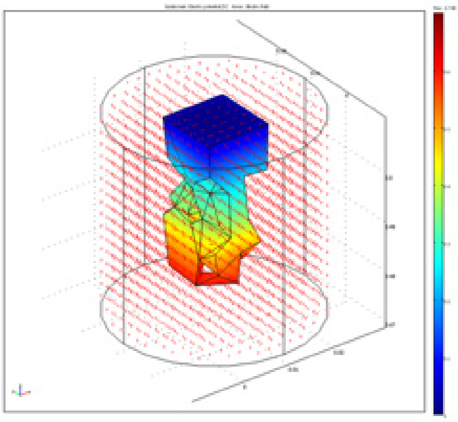

Figure 10. Case 2: The electric potential of 0 V (blue) to 700 mV (red).

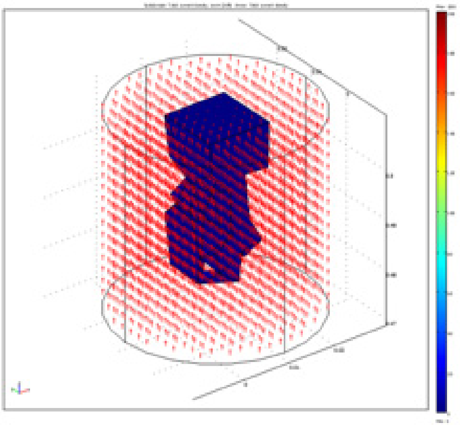

Figure 11. Case 2: The total current density of 0 A/m^2 (blue) to 200 A/m^2 (red).

4. Discussion

Impedance measurements between two electrodes are effected by double layer effects, due to the use of the four point method those effect could be neglected.

The values of the calculated relative permittivity are higher, whereas the conductivity is in same range compared to the values of Gabriel et al. [1, 2, 3].

We assumed that the high permittivities (figure 7) depend on the small frequency of 20 Hz used by the four point method. Subsequent measurements are needed to clarify these test results.

The electric potential distribution demonstrates the way of the voltage from the implant side to the cancellous bone and the cortical bone. We found a different electric potential distribution between figure 8 and 10. The values of the electric parameters, a voltage of 700 mV and a frequency of 20 Hz, were used due to their usage in the BISS implant system. Comparing the total electric current density between case 1 (figure 9) and case 2 (figure 11) shows a increased current density for the case 1 due to the higher conductivity of the bone material compared to case 2.

While the subdomain sectioning according to the experimental measurement was not possible so far and will be part of the future work, the use of the measured electric parameters showed a different current density distribution compared to the published values of Gabriel et al. [1, 2, 3]. The knowledge of spatial bone orientations and local material parameters in conjunction with numerical simulation could provide researchers and implant developers with the necessary information about current density and potential distribution in the surrounding bone tissue to optimize bone stimulation and thereby the therapy effect of implants using electromagnetic stimulation.

5. Conclusion

The numerical simulation of electromagnetic fields with COMSOL of models based on Micro-CT data is a new useful tool to analyzing the presented issues. The methodology and derived electric field data provides a basis for the development of implant systems providing enhanced bone regeneration. Moreover, the results which were obtained from experiment and numerical simulations need to be compared to the existing empirical data. The consideration of the patient specific conductivity would allow an optimization of the parameters for electrostimulation of bone tissue in clinical practice.

6. References

1. C.Gabriel, S.Gabriel and E.Corthout: The dielectric properties of biological tissues: I. Literature survey, Phys. Med. Biol. 41 (1996), 2231-2249.
2. S.Gabriel, R.W.Lau and C.Gabriel: The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz, Phys. Med. Biol. 41 (1996), 2251-2269.
3. S.Gabriel, R.W.Lau and C.Gabriel: The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues, Phys. Med. Biol. 41 (1996), 2271-2293.
4. W. Mittelmeier, S. Lehner, W. Kraus, H. P. Matter, L. Gerdesmeyer, E. Steinhauser: BISS: concept and biomechanical investigations of a new screw system for electromagnetically induced internal osteostimulation. Arch. Orthop. Trauma Surg. 124: 86–91, 2004.
5. K.M. Stuermer, K.P. Schmit-Neuerburg: Indications and clinical results of electromagnetically induced alternating current stimulation of poorly reacting pseudarthroses. Unfallchirurgie 11:197–203, 1985.

7. Acknowledgements

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