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Characterization of human cancellous and subchondral bone with respect to electro physical properties and bone mineral density by means of impedance spectroscopy

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ABSTRACT

Computational simulation of electrical bone stimulation of the electrical and dielectric parameters of osteoarthritic bone tissue is useful for an exact patient-individual adaptation of the bone models. Therefore, we investigated electrical and dielectric parameters at a frequency of 20 Hz of cancellous and subchondral human femoral head bone samples. Furthermore, the mechanical properties and the bone mineral density (BMD) were determined. Finally, these data were compared with the electrical and dielectric parameters. The bone samples were taken from patients with hip osteoarthritis. Electrical conductivity and dielectric permittivity of cancellous bone amounted to 0.043 S/m and $8.1 \cdot 10^6$. BMD of the bone samples determined by dual-x-ray-absorptiometry (DXA) and ashing resulted in 193 ± 70 mg/cm² and 286 ± 59 mg/cm³ respectively. Structural modulus (E_S) and ultimate compression strength (σ_{max}) were measured with 227 ± 94 N/mm² and 6.5 ± 3.4 N/mm². No linear correlation of the electrical and dielectric parameters compared with BMD and mechanical properties of cancellous bone samples was found. Electrical conductivity and dielectric permittivity of subchondral bone resulted in 0.029 S/m and 8.97×10^6.

1. Introduction

Electromagnetic stimulation is clinically used to support bone healing and regeneration [1–4], particularly in case of non-unions and avascular necrosis of the femoral head. Based on the approach of Kraus–Lechner [3], a bipolar induction screw system (BISS) for treatment of avascular head necrosis was proposed [1]. The Kraus–Lechner method applies an electrical field between 5 and 70 V/m, a voltage of 0.7 V and a frequency of 20 Hz on the bone lesions [1,3,5]. Thereby, the patient-individual electric field distribution, especially in the human femoral head, is unknown. In view of the technical design, for development and optimization of electrostimulative implants, information about the bone material properties is required. Electrical and dielectric parameters of the bone tissue have been measured, e.g. by Saha and Williams [6], Gabriel et al. [7–10] and Sierpowska et al. [11]. The data are shown in Table 1.

Saha and Williams [6] determined electrical and dielectric bone parameters of fresh-frozen cancellous and cortical bone of human distal tibia in the frequency range of 120 Hz to 4 MHz at 27 °C and have compared the data with bone density data obtained from ashing experiments (see Table 1). Gabriel et al. [7–10] measured cancellous and cortical bone samples between 10 Hz and 20 GHz at body temperature (37 °C). Bone samples were derived from donors' post mortem. Sierpowska et al. [11] presented data on electrical and dielectric properties of fresh cancellous bone from the human distal femur and proximal tibia using a frequency sweep of 50 Hz–5 MHz at 22 °C. They compared these data with mechanical parameters and bone density.

In a previous study, we created a numerical simulation model of the human femoral head to analyze how different parameters influence the electric field distribution around an electrostimulative implant [12]. However, in computational simulation of electrical bone stimulation, electrical and dielectric parameters of osteoarthritic vs. healthy bone are useful for an exact patient-individual adaptation of the used bone models (Fig. 1). Material

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Table 1
Measured electrical, dielectric and mechanical parameters of human bone material.

	Saha and Williams[a]	Gabriel et al.[b]	Sierpowska et al.[c]
Electrical	Conductivity	Conductivity	Conductivity
Dielectric	Permittivity	Permittivity	Permittivity
Frequency	120 Hz–4 MHz	10 Hz–20 GHz	50 Hz–5 MHz
Temperature	27 °C	37 °C	22 °C
Mechanical	n.i.	n.i.	E-Modulus. σ_{max}
Bone density	Ashing	n.i.	DXA
Human bone specimen	Intraoperatively (distal tibia)	Post mortem	Intraoperatively (distal femur and proximal tibia)
Number of samples (n)	$n = 30$	Unknown	$n = 26$

n.i. = not investigated.
[a] Saha and Williams [6].
[b] Gabriel et al. [7-10].
[c] Sierpowska et al. [11].

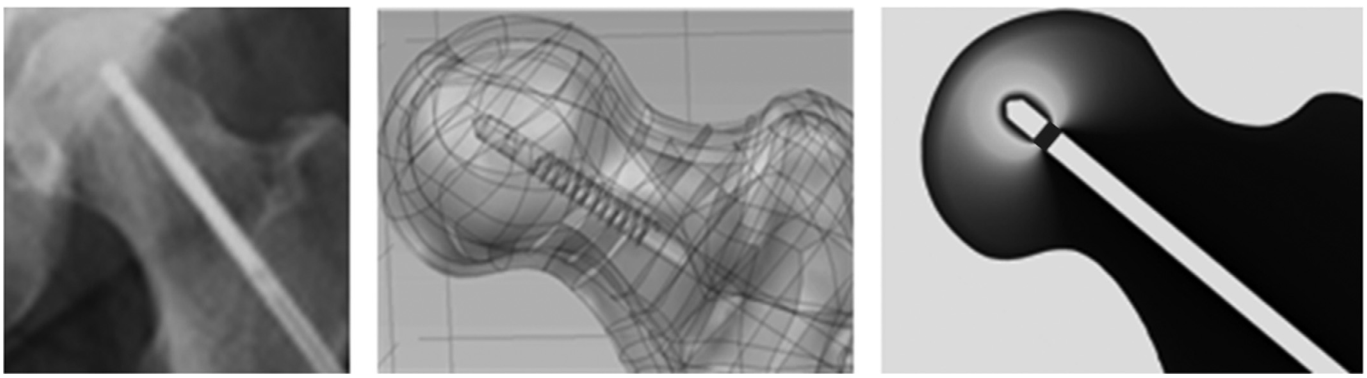

Fig. 1. X-ray image of the implanted ASNIS screw system based on the Kraus–Lechner system [1,3] (left); the schematic computational femoral bone model with electrostimulative implant (middle); the computational simulation of electric field distribution (right).

parameters of electrical conductivity (κ') and dielectric permittivity (ε') of cancellous and subchondral bone of osteoarthritic femoral head are not investigated so far. Furthermore, a correlation between κ' and ε' with mechanical parameters and bone density is missing. Bone samples from osteoarthritic patients include information about electro physical properties of a weak bone.

Therefore, the aim of the present study is to determine the electrical conductivity (κ') and dielectric permittivity (ε') of osteoarthritic bone samples. 20 fresh-frozen cancellous bone samples and 10 fresh-frozen subchondral bone samples, derived from the femoral bone of osteoarthritic patients who underwent total hip replacement, were analyzed in a frequency range between 10 mHz and 10 kHz at body temperature (37 °C). In addition, we investigated the mechanical properties and the bone density of same cancellous bone samples and compared the data with the electrical properties.

2. Materials and methods

2.1. Sample preparation

Human femoral heads were retrieved intraoperatively from 12 female and 8 male donors, aged between 53 and 81 years, and between 60 and 81 years, respectively, who all underwent total hip replacement. Cylindrical samples were cut from each femoral head using a diamond hollow drill (Günther Diamantwerkzeuge, Idar-Oberstein, Germany). The 12 mm diameter drill was positioned on the femoral head at the base of the Ligamentum capitis femoris, aligned with the femoral neck axis. Cylindrical bone samples with a height to diameter ratio between 1 and 2 were used according to DIN 50106 for the mechanical tests. Good reproducibility of the impedance values of the measurements of the osteoarthritic cancellous bone structure was obtained with samples of 12 mm diameter and 15 mm height. The smallest thickness of cancellous bone samples was 3.5 mm. The sample processing is described in detail in Haba et al. [13–14]. Furthermore, 10 subchondral bone samples were obtained from the subchondral region of the femoral head. The height of the cylindrical subchondral bone (12 mm diameter) samples was limited in the present study. The macroscopic height (thickness) of the subchondral bone is associated with osteoarthritis [15] and differs between 1.9 mm and 2.6 mm.

Before testing, the bone samples were kept for 12 h in a refrigerator (+6 °C to +8 °C) and were frozen at −20 °C between the following tests. After thawing, DXA investigations were performed, followed by the analysis of the impedance and mechanical properties and finally by ashing of the bone samples. The tests were approved by the local ethical committee of the University of Rostock (A 2009 38).

2.2. Impedance spectroscopy

We used the impedance spectrometer Broadband Dielectric Spectrometer System BDS 4000 (Alpha high resolution dielectric analyzer) from Novocontrol (Novocontrol Technologies GmbH & Co. KG. Montabaur, Germany). It was equipped with a Quatro Cryosystem from Novocontrol for temperature control and WinDETA software version 4.1. The measuring cell has a parallel disc geometry with two electrodes: one with a diameter of 20 mm and second with a diameter of 40 mm, see Fig. 2. The bone samples were plated with gold leaf (Noris Blattgold GmbH, Schwabach, Germany) in view of a flat surface. Spacers controlled the sample thickness. The material was placed between two gold plated brass plates and heated above the human standard temperature of 37 °C (Fig. 2). The frequency sweeps were performed in the range between 10 mHz and 10 kHz. For impedance measurement on biological materials, to which the used bone belongs, at frequencies below 10 MHz, cells of parallel-plate capacitors are used

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