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Estimation of optimal frequencies for electrical impedance-based diagnosis of osteoporosis based on numerical modeling of cancellous bone tissue

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Abstract
In recent years, the degree of spread of osteoporosis in men and women has increased considerably. According to the existing statistics 20 percent of women above the age 50 are suffering from osteoporosis and the degree of its growth has been more among men rather than women. In the following research, a three-dimensional electrical computer model of cancellous bone tissue has been presented which consists of a unit cell made of cortical bone where we adjust the amount of bone density as desired. Using a commercial electromagnetics simulation software, we put the intended piece under the effect of electric field and calculate the electric current and extract the impedance of the tissue. Considering the fact that the electrical properties of the components of the intended piece is different for each frequency, the obtained impedance would be variable with frequency. Changes of the impedance caused by alteration of the bone density, can thus be computationaly estimated and leads to a model-based estimation of impedance sensitivity to changes in bone density. Consequently, it would be advantageous to find a frequency range that causes the highest relative change in the amount of the impedance as bone density is varied. The obtained results in a wide frequency range of 1 kHz – 1 GHz indicated that by the alteration of the bone density from 10 to 30 percent, the highest sensitivity in the electrical properties of cancellous bone occurres at frequencies less than 100 kilohertz.

Keywords: osteoporosis, impedance meter, osteoporosis, bone density, modeling

Introduction

Osteoporosis is a disease which occurs with a decrease in the density of bones and is a disorder in the microstructure of bone tissue. This disease often occurs above 50 years of age and mostly in women possibly due to decrease in the level of certain hormones [1,2]. Being afflicted by this disease in lower ages can be also triggered by a variety of reasons such as using corticosteroids, hyperthyroidism, lack of calcium consumption and vitamin D, stress and alcohol and cigarette consumption [3−6]. Due to the increase in osteoporosis the probability of bone fracture increases and leads to irrecoverable consequences such as fracture in neck, thighs, spine and pelvis. From what is said, it can be concluded that being aware of the level of bone density and recognizing its changes to prevent the consequences of osteoporosis and treating it is of high importance. We could refer to DEXA (dual energy x-ray absorptiometry) or (Ultrasound densitometry) as density measurement procedures. In this paper, we are looking for a three-dimensional model of bone tissue in order to characterize the relation between a changing bone density and impedance change, and to obtain the relative amount of bone density change in optimized frequency ranges with high accuracy [7,8].

Materials and methods

Cancellous bone is composed mainly of a meshwork of hard bone substance and soft bone marrow. In this work, we build a suitable model according to the structure of the tissue of the bone marrow in a way that the features of each sub-tissue compartment (bone marrow and the hard bony substance which is assumed to be close to cortical bone for electrical properties) are as close to reality as possible. The electrical properties of these constituents are extracted from reports on the dielectric properties of biological tissues [9,10] (figures 1 and 2). First we built a meshwork model directly in the commercial CST (Computer Simulation Technology AG) electromagnetic simulation software, but considering the limited canonical models in obtaining a realistic geometrical model suitable for the tissue, a realistic model was used which has a relatively appropriate similarity with the actual sample (i.e. microscopic figures of the cancellous bone tissue) [11]. Eventually, this model has been imported into the CST software and examined (Fig.3).

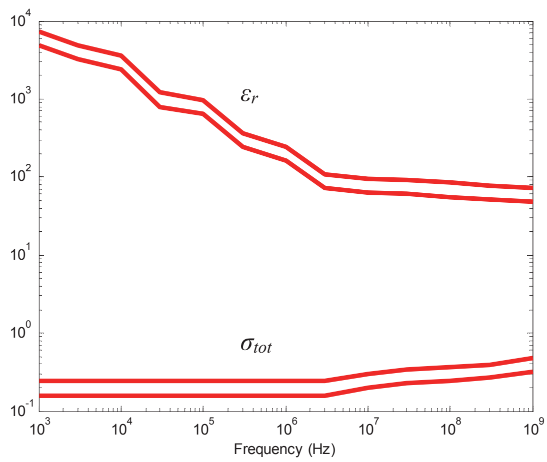

Fig.1: Relative permittivity (top curves) and conductivity (S/m) (bottom curves) of the bone marrow. In the figure above, maximum and minimum permittivity and conductivity limits of bone marrow are shown [9].

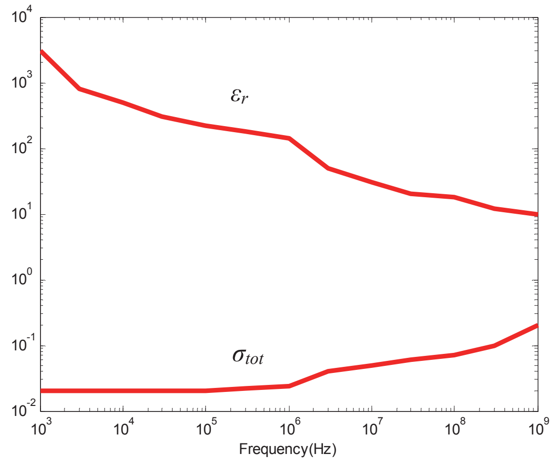

Fig.2: Permittivity (top curves) and conductivity (S/m) (bottom curves) for the cortical bone [10].

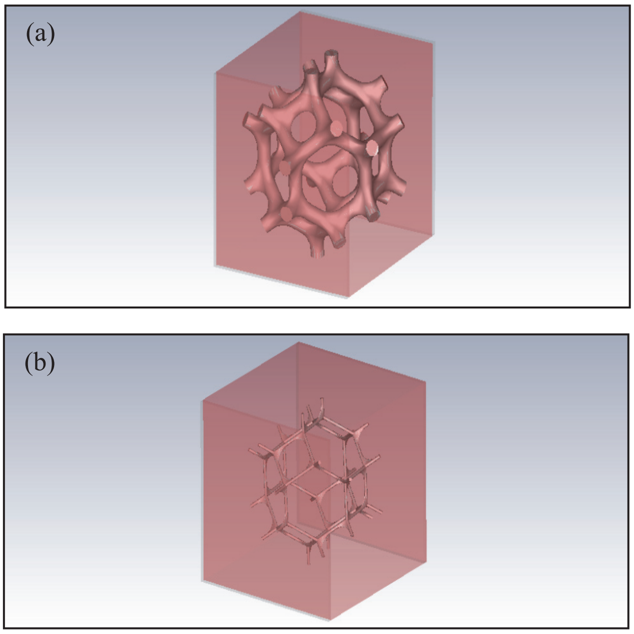

Fig.3: The obtained model of the bone tissue in CST software. Density in the figure (a) is 7% and in the figure (b) is 0.3% [11].

Impedance scanning of the tissue model

The obtained model was entered into the CST software and stimulated by two electrodes that were located on either side of the model, thereby simulating a capacitor model. The features of each tissue in each frequency were specified. Afterwards, by calculating the total current using integration on the plane normal to the direction of current, the impedance of the tissue has been calculated. The A/d ratio has been 3.1 mm for the current simulation in figure 3.

$$Y = \frac{I}{V} = \frac{1}{Z} = \sigma_{tot}\frac{A}{d} + j\omega\varepsilon_0\varepsilon_r\frac{A}{d} \qquad (1)$$

Model based electrical properties of the tissue and verification with experimental results

According to the formula (1) and calculating the current, the effective (homogenized) value of ε_r and σ_{tot} for the whole tissue can be calculated for each frequency. In the graph below, these amounts have been calculated for 30% bone density and compared with the experimental data obtained by Gabriel [10] for cancellous bone. The difference of the two model graphs in figure 4 is due to uncertainty of the features of the bone marrow (as given in figure 1).

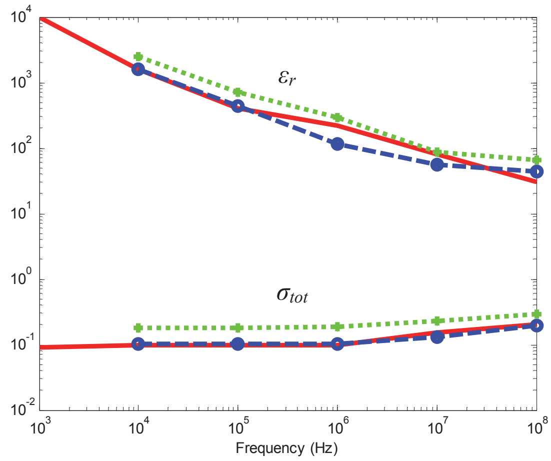

Fig.4: Comparison of the permittivity and conductivity (S/m) obtained from the results of our model and properties of cancellous bone extracted from [10]. Dotted and dashed curves are model results corresponding to maximum and minimum properties of the bone marrow tissue, compared with experimental results of [10] which is shown with solid line.

As is obvious in figure 4 the results obtained from the models, have relatively high accordance with experimental results, so that next, the verified numerical model will be used in examining the changes of the impedance (permittivity and conductivity of tissue) with the alteration of bone density.

Results

We recomposed the model according to 10 to 30 percent bone densities for different frequencies and computed the relative change in the electrical properties for each frequency based on simulations of the model (figure 3). As is indicated in figure 5, percentage of changes are maximal up to 100 kHz frequency. The percentage of change of the admittance (or impedance) has been defined as the difference of the admittance (impedance) at 10 and 30 percent bone densities as divided by the admittance (impedance) value at 10 percent density.

$$\text{Percentage of change in admittance} = \frac{Y_{30\%} - Y_{10\%}}{Y_{10\%}} \qquad (2)$$

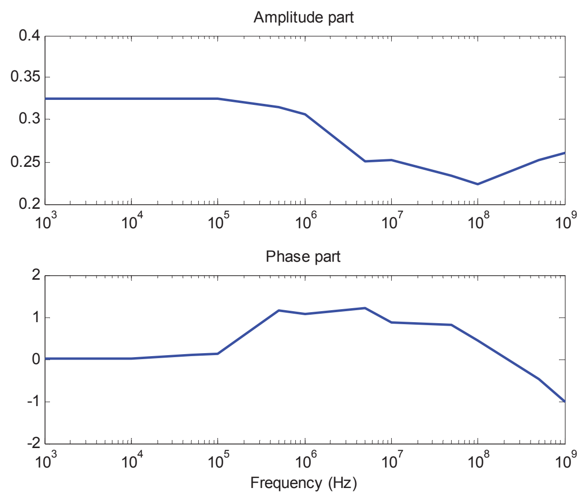

Fig.5: The percentage of the admittance change according to a 20% change of bone density from 1kHz to 1GHz.

Table 1: Admittance (Y=1/Z) for 10 percent bone density

Frequency (Hz)	Admittance (mS)	
	Real Part	Imaginary Part
1K	0.9340	0.0017487
5K	0.9340	0.005356
10K	0.9340	0.007956
50K	0.9340	0.0138023
100K	0.9340	0.0219348
500K	0.9369	0.0450018
1M	0.9399	0.0615236
5M	0.9604	0.1330
10M	1.2003	0.2274
50M	1.3490	1.0398
100M	1.4517	1.9395
500M	1.6251	8.8706
1G	2.0659	16.3413

Table 1: Admittance (Y=1/Z) for 30 percent bone density

Frequency (Hz)	Admittance (mS)	
	Real Part	Imaginary Part
1K	0.7049	0.0016069
5K	0.7049	0.004280
10K	0.7049	0.0062451
50K	0.7049	0.0116188
100K	0.7049	0.0182412
500K	0.7115	0.048474
1M	0.7181	0.0604440
5M	0.7652	0.1226
10M	0.9561	0.1963
50M	1.0818	0.8582
100M	1.1740	1.5945
500M	1.3562	7.0695
1G	1.8717	12.9255

We can define sensitivity as the ration of relative differences in Y as in (2) and similarly for bone density (D); i.e.

$$\frac{\delta Y}{\delta D} = 0.165 \qquad (3)$$

We can thus expect a sensitivity of about 0.165 for frequencies below 100 kHz.

Discussion and conclusion

In this paper, we have presented a numerical model appropriate for the structure of cancellous bone by which the electrical properties of the bone tissue could be calculated for different bone densities in frequency ranges from 1 kHz to 1 GHz.

First, physical features of the obtained model, such as conductivity was compared with the experimental data for cancellous bone in order to verify the accuracy of the presented model. Afterwards, the density of the tissue was increased from 10% to 30% (a two-fold relative change) and the degree of change in the impedance at different frequencies was calculated. Then, the amount of impedance alteration following an alteration of the bone density in each frequency were presented in the form of a graph (figure 5). According to these results, any measure proportional to the electric properties of cancellous bone at frequencies lower than 100 kHz leads to a better estimation of the alterations in bone density.

To explain this effect, we can refer to the electrical properties of the components of the sub-tissues that form the cancellous bone.

The amount of the conductivity of the cortical bone (used to model the mesh work of hard material in cancellous bone) is almost fixed up to 100 kHz and is equal to 0.02 S/m and the conductivity of the tissue of the bone marrow is equal to 0.2 S/m, while these amounts increase up to 0.2 and 0.4 at higher frequencies; thus, considering the fact that up to 100 kHz the conductivity of cortical bone is about 10 times lower than that of bone marrow, the alteration of bone density causes a higher degree of change in the bone impedance below 100 kHz in comparison with higher frequencies.

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