

Researches of mechanical behavior of bone tissues for development and selection of individual ceramic implants

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Abstract. The researches of mechanical behavior were conducted and the effective mechanical properties of model compact bone micro volumes under uniaxial compression were obtained taking into account the structural characteristics and the mineral content; experimental analysis of the mechanical behavior and the effective mechanical parameters of obtained porous zirconia ceramics were conducted. The comparison of obtained in paper calculated and experimental mechanical properties of bone and ceramics was carry out and the recommendations on the use the ceramics with certain porosity to replace the compact bone fragment with a certain structure and mineral content were suggested.

1. Introduction

Many years of experience in the use of artificial materials to restore elements of the bone through the endoprosthesis replacement indicates that the biochemical compatibility of implant with the organism is necessary but not sufficient condition for the functioning of the implant - bone system as a whole. Important condition is the biomechanical compatibility of implant and bone. It is known that a significant difference in the elasticity of bone and the implant can result in the loss of the latter due to the subsequent resorption of a bone tissue in contact with implant. For Creation of artificial materials that meet the conditions of biomechanical compatibility with bone, requires as much as possible a better understanding of the mechanical behavior of the replaced bone fragment, that defined by its hierarchically organized structure [1-5].

The mechanical behavior and mechanical parameters of model fragments of compact bone under uniaxial compression with consideration structural features and mineral content were studied; the experimental studies of the mechanical behavior and mechanical parameters of porous zirconia ceramics also have been executed.

2. Materials and methods

Geometrical model of compact bone tissue is constructed on basis of a real image of the microstructure of compact bone [6] (Figure 1, Figure 2).

The model microvolume of compact bone contain the osteons and Haversian canals, the matrix and cement line that separates osteons from the matrix (Figure 3).

The total porosity of the compact bone fragment P determined by Haversian canals which are modeled explicitly (Figure 4), and by Volkmann's canals, which taken into account implicitly in the calculation of the effective mechanical characteristic of the structural components of the model microvolume.



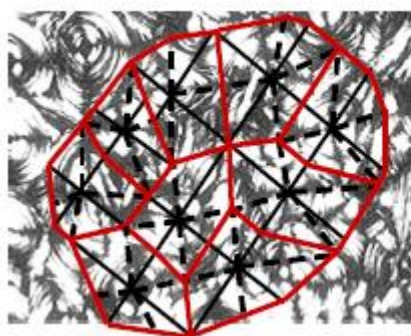


Figure 1. Division of picture of compact bone microstructure on the structural elements

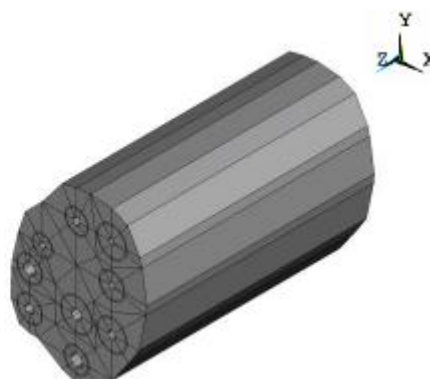


Figure 2. Geometrical model of compact bone tissue

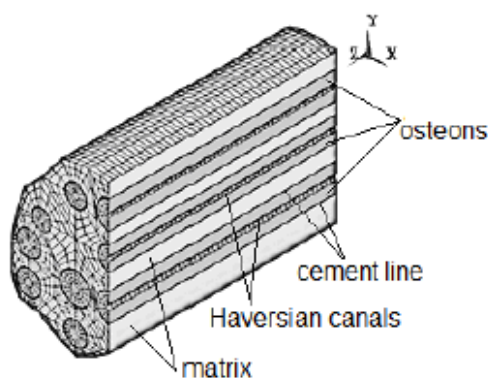


Figure 3. Finite element model of compact bone tissue

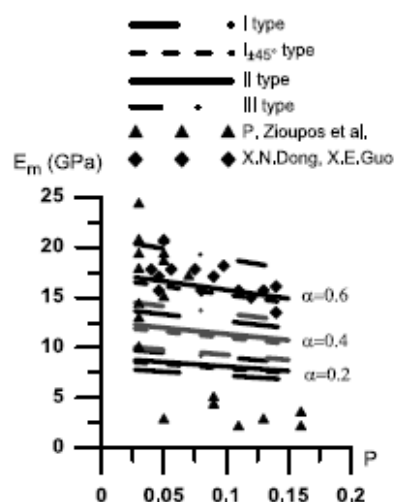


Figure 4. The dependence of the longitudinal modulus of elasticity of compact bone fragments of different types with different mineral content α from porosity

The material of structural components of the model microvolume compact bone was considered transversely isotropic. Effective mechanical properties of the matrix material and the reinforcing elements, osteons, are calculated taking into account the volume fraction of collagen and mineral component, the orientation of collagen and mineral fibers, the porosity due to the presence Volkmann's canals.

Calculations of the stress-strain state of the model compact bone fragments were performed in the software package ANSYS.

Microvolume was subjected to axial compression along the axis Z. In Figure 2, the plane of loading is shown in the foreground, plane of fixing in the background. The problem was solved in the framework of the linear theory of elasticity.

Samples of ceramic were prepared from the finely divided powder of zirconia partially stabilized with yttrium oxide, with a porosity of 10 to 70% obtained using pore-forming material. Uniaxial

compression tests were carried out according to standard procedures on a universal testing machine "Instron-1185" with a constant loading rate $3 \cdot 10^{-4}$ s-1.

3. Results and Discussion

Figure 5 shows the results of calculations of longitudinal modulus of elasticity of compact bone fragments with different directions collagen-mineral fibers (I type - transverse fibers, I $\pm 45^\circ$ type - fibers are arranged at angles of $\pm 45^\circ$ in adjacent lamellas of osteon, II type - fibers orientation change with a perpendicular to the parallel to the bone axis, III type - longitudinal fibers) with different mass fractions α of minerals and porosity P at axial compression in comparison with the experimental results P. Zioupos et al. [7], XN Dong, XER Guo [5].

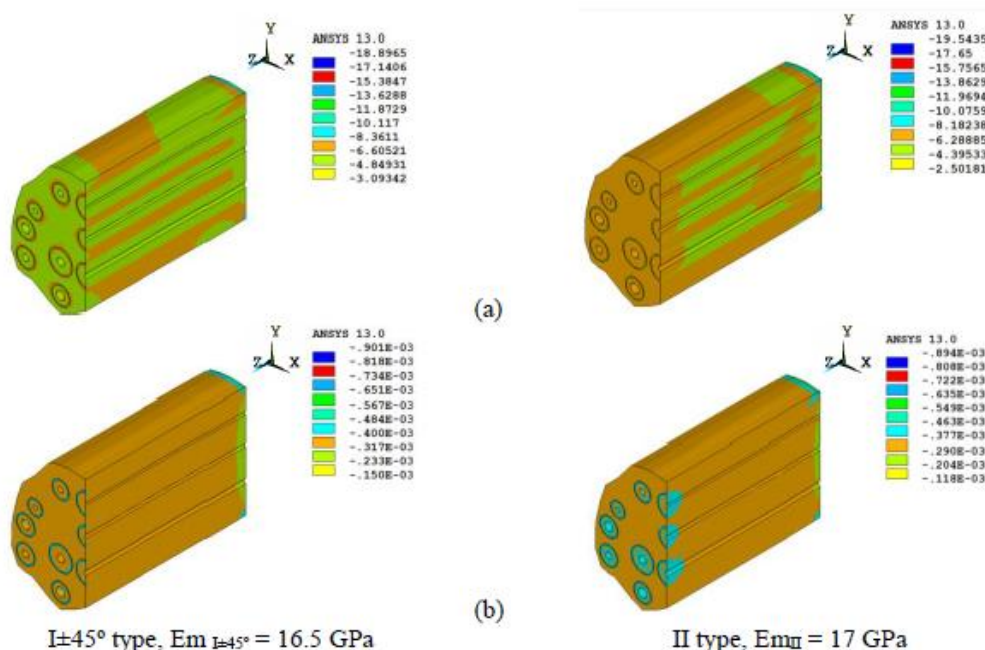


Figure 5. Distribution of the stress a) σ_z (MPa), and strains b) ϵ_z in model microvolumes of compact bone tissue of different types with $P = 0.027$, $\alpha = 0.6$, which were clipped by YZ plane, at compressive stress $\sigma_m = -6.5$ MPa

The cortical bone microvolumes of I $\pm 45^\circ$ type and type II regardless from their porosity P have the same longitudinal modulus of elasticity (E_m), but differ in the nature of the distribution of stresses a) and strains b), that is determined by various non-uniform deformation response of microvolumes in mutually perpendicular directions relative to the direction of load action, i.e., in the directions of axes X and Y.

This result demonstrates the need of accounting of effective parameters responsible for the nature of the distribution of stresses and strains of bone tissue.

As a result of the tests on uniaxial compression of zirconia ceramic ZrO_2 (Y_2O_3) were obtained dependence of longitudinal modulus of elasticity and ultimate compressive strength of the ceramic samples from the specific volume of pore θ .

Comparison of the calculated modulus of elasticity and the ultimate compressive strength of bone microvolumes, calculated using the Hernandez formula [8], and the experimentally obtained mechanical characteristics of ceramic (Table 1) showed that the ceramics with a pore volume from 50 to 60% has the same modulus of elasticity as a compact bone with mass concentration of minerals from 40 to 55% and a porosity from 3 to 15%.

Table 1. Calculated and experimental effective mechanical properties of compact bone and ceramics

Ceramics $\text{ZrO}_2(\text{Y}_2\text{O}_3)$ (experiment)				Compact bone (calculation)			
θ	E, GPa	σ_c , MPa	α	P	Type	Em, GPa	σ_c , MPa
0.50	16.87	110.0	0.55	0.15	III	16.4	109.7
0.52	15.50	98.0	0.50	0.10	III	15.8	93.8
			0.45	0.027	III	15.5	81.2
0.54	14.17	87.3	0.45	0.15	III	13.7	62.7
			0.40	0.027	III	14.2	58.5
0.56	12.98	77.7	0.40	0.10	III	13.2	50.3
			0.40	0.15	III	12.6	45.1
0.58	11.89	69.2	0.45	0.15	II	11.6	62.7
			0.40	0.027	I \pm 45°	11.9	58.5
0.60	10.89	61.6	0.40	0.15	II	10.7	45.1
			0.40	0.15	I \pm 45°	10.5	45.1

4. Conclusion

The ceramics with porosity 50-56% may be candidate for replacement of compact bone fragment with the location of the collagen- mineral fibers parallel to the axis of the bone (III type), and the ceramics with a porosity of 58 to 60% may be candidate for replacement of the compact bone fragment with the direction of collagen-mineral fibers, which change the orientation of the transition from one lamella to another (II type), or placed at angles of ± 45 degree(I \pm 45 type).

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