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IMPACT OF MINERAL CONTENT IN HUMAN TRABECULAR BONE ON ITS STATIC AND FATIGUE PROPERTIES

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Abstract: *The paper presents results of static and fatigue strength, and mineral content for 60 trabecular bone samples. The samples were collected from human femoral heads after alloplastic treatment of femoral head, of patients suffering from coxarthrosis and osteoporosis. Evaluation of mineral density of the bone - BMD, and ash density - Ash.D were performed. Static and fatigue strength of the bones was determined through compression test. Fatigue compression test was performed with stepwise increasing amplitude. The results obtained suggested correlation between BMD, Ash. D and the results of static and fatigue test. The relations obtained, evaluated using R correlation coefficient, fell within the range R = 0.70 – 0.75. The results confirmed the usability of BMD and Ash.D indicators for evaluating static and fatigue strength of trabecular bone.*

Keywords: Trabecular bone, Static compression test, Fatigue compression test, Ash density, BMD.

1. Introduction

Bones form the human skeleton, serving supporting functions for the body. Together with the muscles and ligament system, they form the motor system of human. Due to its structure, and the specifics of daily activity of man, the majority of bones is subjected to compression loads. Human bones are a composite material built of organic and mineral materials of different properties, and of different physical state. The components include compact bone, trabecular bone, articular cartilage, bone marrow, blood, nerve fibres, blood vessels, bone cells and periosteum. One of the components, the trabecular bone, is one of the factors mostly decisive for its strength. Its quality and quantity changes quicker than with the remaining components, which causes the strength of bones to also change. One of the factors determining bone strength is mineral content (Mosekilde et al., 1987 and Kang et al., 1998). The assessment of mineral content allows to prognose bone strength. Therefore, the aim of this paper was to assess the impact of mineral content in the trabecular bone on its static (marked as US) and fatigue (marked as Ns) strength. The strengths were determined through compression test. Due to the fact that the variable stresses to which the bone is subjected are of low-cycle nature - below 1 Hz (Yuehuei et al., 1999 and Covin, 1999), the fatigue test was performed in the examination with stepwise increasing amplitude. This allowed to reduce the time necessary to perform the examinations.

Mineral content in the bone is difficult to determine "in vivo". The basic examination used for this type of assessment is densitometric examination. One of the indicators used in evaluations is bone mass density – BMD. During "in vitro" examinations, such indicator is ash density - Ash.D. Both of these indicators were used to assess mineral content in trabecular bone, and the results obtained were correlated with results obtained from static and cyclic strength tests.

2. Methods

60 samples of human femoral head of 10 mm diameter and 10 mm height were used. The samples were cut from femoral heads obtained as a result of implanting hip joint of patients with osteoporosis and coxarthrosis. The age of the patients ranged from 49 to 84 years with an average of 71 years. The samples were split into two groups, 30 pieces each. The number of samples originating from ostheoporotic and coxarthrotic bones was not the same, therefore the authors assigned to each test group an equal number of

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samples of the same type. One group was used to test static strength, while the other was used for cyclic tests. The samples were not divided according to the type of disease or the age of patients. The samples were stored in 10 % formalin solution at the room temperature. Fig. 1 presents the method of cutting samples from the femoral head (Topolinski et al., 2011).

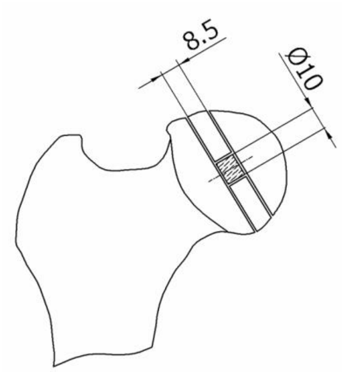

Fig. 1: Samples collecting scheme.

BMD measurement was performed using a clinic-grade densitometer type Lunar Expert (General Electric), according to the procedure specified by the manufacturer in the technical documentation of the device for bone mass density measurements on bone samples performed "in vitro".

Instron 8874 (Instron Company) machine was used to perform compression and fatigue tests. During measurement of static strength, the sample was placed in a strength testing machine between working surfaces of the machine. Then, five initial cycles were performed in order to obtain deformation value $\varepsilon = 0.5$ % of sample height, to stabilize the contact surface between head surfaces of the sample and working surfaces of the machine. The duration of one loading-unloading cycle was 30 seconds. The interval between the cycles was 5 seconds. Then, the test was performed at fixed deformation speed equal to 0.1 mm/min. The value of compression strength corresponded to the moment of occurrence of the first maximum on the compression curve, i.e. when strength is starting to visibly lower for the first time, at fixed rate of increase of deformation (Gibson, 1985) The test was performed in room temperature.

The fatigue tests were carried out under load with stepwise increasing loading. The frequency of sinusoidal loading was 1 Hz. The minimum loading for all the loading levels was 5 – 7 N, maximum loading started from 20 N at first step with a gain every 10 N at successive steps. Each level of load maintained 500 cycles realized under constant amplitude loadings. The test was conducted in constant temperature 37 ± 2 ºC in 0.7 % NaCl water solution (Winwood et al., 2006 and Brouwers et al., 2009). Program of the test is presented in Fig. 2. Fatigue life (Ns) was estimated using modification method described by Bowman et al. (1998). In this purpose determined the median values of deformation increment of sample. Assumed that fatigue life is defined as: number of the first loop for which value the deformation gain exceeded the value of the median by 10 % (Topolinski et al., 2011). Fig. 2 presents the test program.

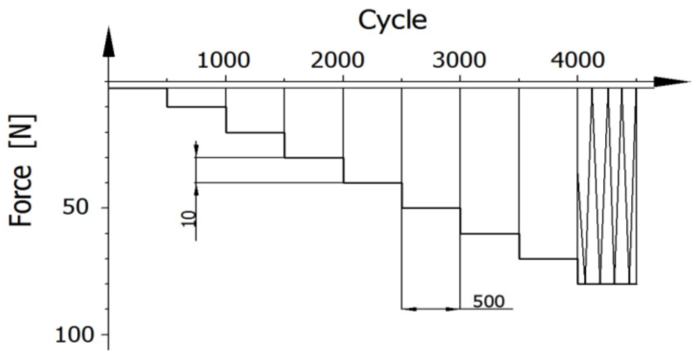

Fig. 2: Cyclic test program.

Before the ash density measurement, the samples were dried for 24 hours in 120 ºC, and then weighted. After this, they were placed in a furnace for 18 hours in 800 ºC temperature (Yuehuei et al., 1999). Then, they were weighted again. After dividing the mass of each sample after burning by its volume before burning, Ash density in g/cm^3 was obtained.

Also, mineral content of dry sample, marked as % Min, and defined as the quotient of sample mass after drying and burning was measured and expressed in percentage.

3. Results

Tab. 1 presents the results of measurements performed in the form of a range of obtained values, average value and the value of standard deviation, relative standard deviation and distribution. BMD, Ash.D and % Min values were specified separately for both groups of the samples tested. Normality of distribution of results was checked by Shapiro-Wilk tests, with p = 0.05 value. Tab. 2 presents the values of correlation coefficient R between BMD, Ash.D, % Min and static and cyclical strength.

Tab. 1: Values of density and static and cyclic strength.

	BMD [g/cm^2]	**Ash.D** [g[/cm^3]	**% Min** [%]	**US** [MPa]	**BMD,** [g/cm^2]	**Ash.D,** [g/cm^3]	**% Min,** [%]	**Ns** [n]
Test	**Static**				**Fatigue**			
Min	0.135	0.173	20.7	1.68	0.094	0.174	37.7	1185
Max	0.436	0.514	47.3	36.14	0.522	0.617	101.3	50535
Av	0.295	0.322	35.8	12.46	0.275	0.326	57.3	20649
SD	0.085	0.088	6.4	7.96	0.091	0.095	8.1	11671
RSD [%]	28.8	27.3	17.9	63.9	33.1	29.1	14.1	56.5
Dis	N	N	N	logN	N	logN	logN	N

where:
Min – minimum.
Max – maximum.
Av – average.
SD – standard deviation.
RSD – relative standard deviation.
Dis – distribution: N –Normal, LogN – logNormal (veryfied by Shapiro-Wilk tests, p = 0.05)

Tab. 2: Values of the correlation coefficients obtained between static - US, fatigue - Ns strength and different indicators of density.

	BMD [g/cm^2]	**Ash.D** [g/cm^3]	**% Min** [%]
US [MPa]	0.70	0.71	0.57
Ns [n]	0.74	0.75	0.22

4. Conclusions

The results of measurements of indicators describing bone density, i.e. BMD and Ash.D are similar, taking into account the average value in tested groups, and the value of standard deviation. This suggests that the groups tested were selected properly. The results obtained both for static and fatigue strength exhibited a larger dispersion, which is suggested by the values of relative standard deviation.

While the defining of strength in the static compression test is clear and unequivocal, it is not so simple in case of fatigue test with gradually increasing amplitude. An appropriate sample destruction criterion must be adopted here. This criterion was created and adopted based on paper Bowman et al. (1998). For constant-amplitude fatigue tests, fatigue strength, i.e. the sample destruction moment is assumed to be the number of cycles after which the loss of elastic modulus by 30 % compared to the first cycles occurs (Covin, 1999). In tests with gradually increasing amplitude the issue is not so simple, and it is very important to correctly choose this criterion, not to make mistakes in assessing fatigue strength.

The values of correlation coefficients presented in Tab. 2 are insignificantly higher for fatigue strength than static strength. The reason for this may be that the static test was performed in room temperature, while the fatigue strength was performed at human body temperature. Nevertheless, this approach is conformant with literature, since the difference in results of static strength for bone tests performed in room temperature and human body temperature does not exceed 5 % (Carter et al., 1976). Despite the fact that the described results should not differ significantly, this could have had an insignificant impact on the obtained results static test, and on the value of correlation between them.

Correlation between the percentage content of minerals in dry mass of the sample, and the strength is much smaller, and non-existent in case of fatigue strength. This probably results from the fact that this indicator refers to mineral content in dry mass, and the measurement static and fatigue strength were performed on wet samples. Removal of humidity from the samples prior to measuring % Min indicator could change the strength of correlation between its value, and the values of static and fatigue strength.

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