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Investigation of bone tissue mechanical properties in the supra-acetabular region

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Abstract

Introduction The investigation of the trabecular bone strength in the acetabular area and its dependence on age and gender may provide a theoretical basis for the development of implants for bone replacement. **The purpose** of this study was to determine the mechanical characteristics of the bone tissue in the supra-acetabular region in patients of different age groups. **Materials and methods** The cadaveric material of 60 patients was studied and included 20 young patients (age range, 18 to 44), 20 middle-aged patients (age range 45 to 59) and 20 elderly patients (age range, 60 to 74). Fragments of bone tissue 3 × 3 × 1.5 cm in size were removed from the supra-acetabular region using an osteotome. Cylindrical specimens, 6 mm in diameter and 9 mm high, were produced from these fragments using a crown cutter. All samples were subjected to uniaxial compression at a loading rate of 1 mm/min. **Results** Comparison of male patients for each of the mechanical parameters did not reveal age differences ($p > 0.05$). In women of different age groups, the magnitude of elastic deformation was significantly different both by multiple analysis and in pairwise comparison of groups ($p < 0.05$). There was also no statistically significant difference in the maximum stress and modulus of elasticity in women ($p > 0.05$). **Discussion** The data obtained on the mechanical behavior of the trabecular bone and the values of the strength parameters are explained by the spatial arrangement of the fibers of structural proteins, the cross-linking profile of collagen, the degree of matrix mineralization, the structure of hydroxyapatite, and the amount of bound water. Conclusion In male patients, mechanical characteristics of the bone tissue in the supra-acetabular region do not change significantly with age. In women, the value of elastic deformation increases significantly with age. The maximum tensile strength and modulus of elasticity in women of different ages did not show any changes.

Keywords: trabecular bone tissue, supra-acetabular region, mechanical properties, uniaxial compression, hip arthroplasty

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INTRODUCTION

In surgical interventions on the hip joint, the problem of managing bone defects in the acetabulum is essential for ensuring stable fixation of the pelvic component of the endoprosthesis or adequate osteosynthesis in case of injury [1–4]. The problem of age-related osteoporosis, as well as a decrease in bone quality due to severe somatic and systemic diseases of the connective tissue, remains relevant for orthopedic traumatologists. The low modulus of elasticity of bone tissue significantly limits the physician in the choice of osteoplastic materials, endoprosthesis components, fixators for osteosynthesis [5–7].

The study of the average mechanical parameters of bone strength in patients in regard to age and gender may enable to create a theoretical basis for the development of both customized bone-replacing structures and for designing the production of such medical devices on an industrial scale [8, 9]. The point of maximum stress is a characteristic that determines the maximum load that the bone can withstand without breaking. Young’s modulus characterizes the stiffness of a material under elastic deformation. The stiffer is the sample, the greater is the load that must be applied to it in order to deform it. The value of elastic deformation determines how much a sample can be deformed without irreversible changes in its microstructure [10]. All of the above characteristics should be taken into account when developing materials (titanium, ceramics) for filing the defects in trabecular (spongy) bone tissue in order to prevent perifocal bone resorption due to higher mechanical properties of artificial materials compared to the patient's bone [11–14].

The purpose of this study was to determine the mechanical characteristics of the bone tissue of the supra-acetabular region in individuals of different age groups.

MATERIAL AND METHODS

The collection of the material was carried out on the basis of the patho-anatomical department of the MAU Central Clinical Hospital No. 24 in Yekaterinburg. The study was approved by the local ethics committee of the Ural State Medical University (protocol No. 9 of 10/22/21). The inclusion criterion was the age corresponding to the objectives of the study; the exclusion criterion was the presence of severe pathology of the hip joint (coxarthrosis stage 3 to 4). The cadaveric material of 60 persons of both sexes was studied: 20 young subjects (age, 18 to 44 years), 20 middle-aged subjects (age, 45 to 59 years) and 20 elderly persons (age, 60 to 74 years). The age grouping was carried out according to the WHO classification. The study included material from 13 men and 7 women of young age, 11 men and 9 women of middle age, 9 men and 11 women of advanced age. Fragments of bone tissue approximately 3 × 3 × 1.5 cm in size were removed from the supra-acetabular area using an osteotome. Three cylindrical specimens, 6 mm in diameter and 9 mm high, were produced from these fragments using a crown cutter. The cutter was oriented perpendicular to the articular cartilage. The compression surfaces of the specimens were ground with a diamond disk until they were plane-parallel. The dimensions of bone cylinders were measured with a micrometer (error 0.01 mm). The specimen preparation process is shown in Figure 1.

All specimens were subjected to uniaxial compression at a loading rate of 1 mm/min. The direction of force application corresponded to the physiological load of the bone of a given localization. The experiment was carried out using a Shimadzu AG-X50kN tensile/testing machine (Japan). For conducting the test, the lower platform of the testing machine remains stationary; the tension is created by the movement of the upper plate at a given constant speed.

Statistical analysis of the data was carried out using the Statistica 8.0 software. The normality of the distribution was assessed using the Kolmogorov-Smirnov test. Verification of the results of determining the modulus of elasticity, maximum tension stress and elastic deformation using this criterion revealed the lack of normal distribution of the data obtained both in the study of the material of males and females. Therefore, non-parametric criteria were used. To determine the significance of differences between the groups, the Kruskal-Wallis test was used; pairwise comparison of groups was performed using the Mann-Whitney test.

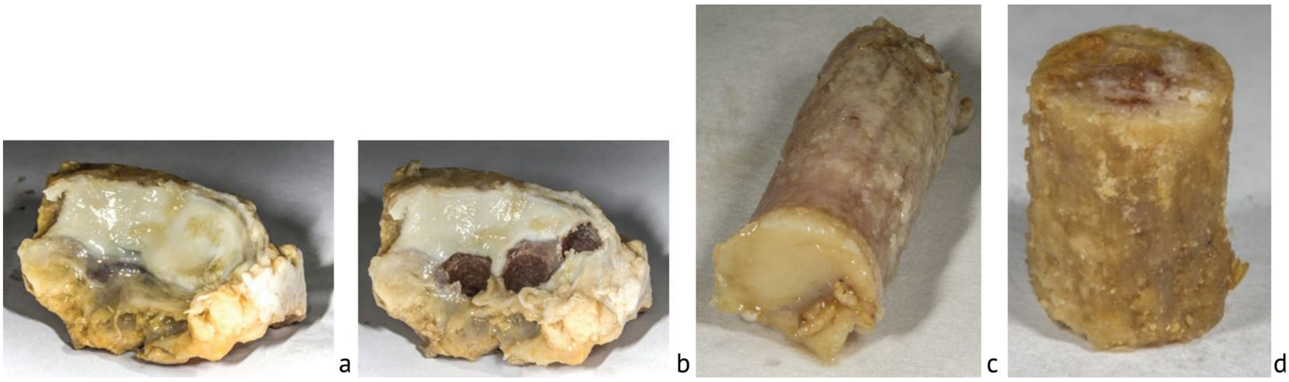

Fig. 1 Stages of preparation of specimens for mechanical tests: ***a*** fragment of bone tissue from the supraacetabular region; ***b*** fragment of bone tissue after reaming; ***c*** cylindrical piece with a fragment of articular cartilage; ***d*** finished sample for mechanical testing

RESULTS

The data on the mechanical properties of the bone tissue of the supra-acetabular region of males and females in different age groups are presented in Table 1.

Table 1

Mechanical properties of the supra-acetbular bone tissue specimens obtained from males and females of different age group (WHO classification). Data are presented as medians (interquartile range]

Age group	Sex	Young age (18–44 years old)	Middle age (45–59 years old)	Elderly (60–74 years old)	p1
Modulus of elasticity, GPa	males	0.10 [0.05; 0.27]	0.11 [0.09; 0.16]	0.13 [0.11; 0.18]	0.619
	females	0.13 [0.09; 0.23]	0.17 [0.05; 0.22]	0.07 [0.04; 0.12]	0.172
p2		0.445	0.668	0.016	
Ultimate tensile strength, MPa	males	3.08 [1.97; 4.98]	2.98 [1.97; 4.14]	3.49 [2.77; 5.09]	0.770
	females	3.06 [2.67; 5.70]	3.84 [1.92; 7.13]	3.23 [1.86; 3.66]	0.886
p2		0.744	0.646	0.681	
Elastic deformation, %	males	3.57 [3.15; 4.30]	4.14 [3.38; 5.16]	3.55 [2.82; 5.64]	0.568
	females	3.36 [2.96; 4.08]	4.45 [4.11; 6.52]	9.98 [5.93; 12.44]	0.003
p2		0.326	0.330	0.007	

Pairwise comparisons between the groups revealed differences in the samples of younger and older women, p = 0.002.
Note: p1 – Kruskal-Wallis test (comparison between age groups); p2 – Mann-Whitney test (comparison between men and women)

Comparison of male samples of young, middle and old age in terms of modulus of elasticity, maximum tensile strength and elastic deformation did not reveal age differences in any of the mechanical parameters.

In the material of women of different age groups, no significant differences were found in determining the maximum stress and modulus of elasticity. At the same time, a multiple comparison of groups revealed significant differences in the magnitude of elastic deformation. Conducting a further pairwise comparison of the groups showed the presence of significant differences in this indicator in the samples of women of young and old age.

Under the compression load, there was no breach of the specimen into separate fragments. There was its gradual flattening with a decrease in height and increase in diameter. Thereby, the reduction in height was not even along the entire volume. Changes were more considerable in the upper specimen part, closer to its surface (Fig. 2 and Fig. 3).

No difference in mechanical properties between the male and female bone were revealed in young and old age groups. In elderly, the male bone exceeded the female one in strength (the modulus of elasticity was significantly higher). Female bone tissue in elderly group was easier deformed but featured more ability to recover its initial shape than the male bone tissue (the value of elastic deformation was significantly bigger).

In the young and middle-age groups, there were no differences between the male and female bones in terms of mechanical properties. In old age, the male bone significantly exceeded the female one in terms of stiffness (the modulus of elasticity is significantly higher). The bone tissue of elderly women was more easily deformed, but had a greater ability to restore its original shape than male bone tissue (the magnitude of elastic deformation is significantly higher).

The deformation curve shows the dependence of tensile strength in the bone tissue on the value of deformation. In the graph, compiled for the trabecular bone tissue of the supra-acetabular region under uniaxial compression, there is a section characterizing the elastic properties of the bone (linear section). This is followed by a significant portion where the deformation is irreversible. At the same time, slight periodic fluctuations in the tension in the bone occurred in this area (Fig. 4, 5).

The above regularities in the mechanical behavior of the specimens are typical for both male and female bones.

Fig. 2 Initial specimen

Fig. 3 The specimen upon completion of the mechanical test for uniaxial compression

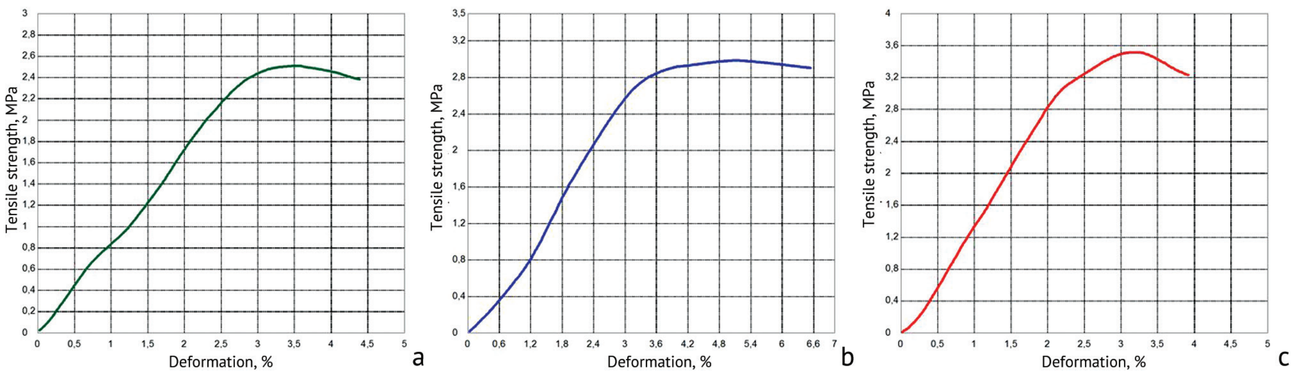

Fig. 4 Graphs of deformation behavior of bone tissue samples harvested from males of different age groups: ***a*** young age; ***b*** middle age; ***c*** elderly persons

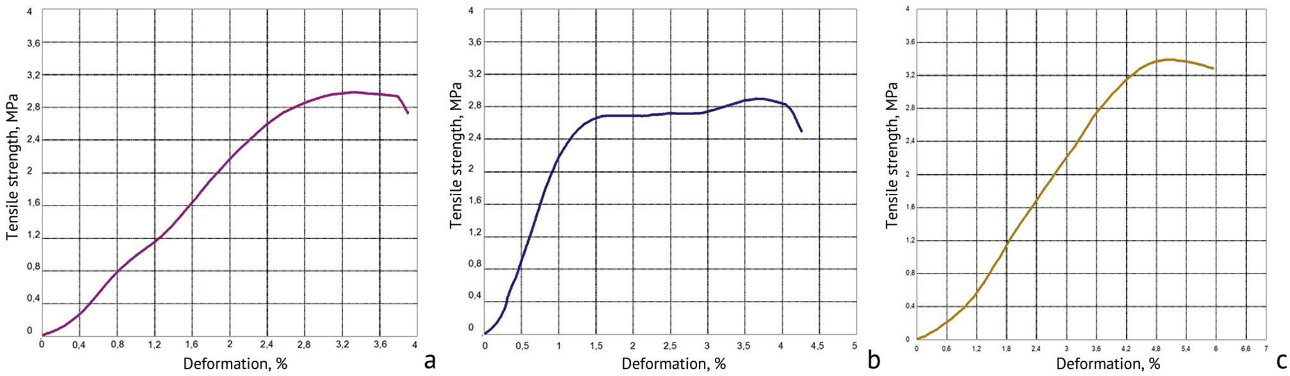

Fig. 5 Graphs of deformation behavior of bone tissue samples harvested from females of different age groups: ***a*** young age; ***b*** middle age; ***c*** elderly persons

DISCUSSION

Due to heterogeneity of the main bone tissue components (organic matrix and minerals), the relationship of mechanical properties at the local tissue level and general strength to breach is difficult to quantify [15, 16]. The presupposing determinants of the mechanical behavior of bone tissue include collagen orientation profile of collagen binding, mineralization grade or the ratio of the minerals to matrix, bound water and mineral structure. However, such properties such strength and plasticity, according to Hart N.H., Nimphius S., Rantalainen T., Ireland A. et al (2017), depend on the volumetric characteristics of porosity and the method of connecting the organic and inorganic components of the bone tissue to each other [17].

Mechanical properties of the bone at the tissue level, according to the results of studies by Nyman J.S., Granke M., Singleton R.C. et al (2016) and Morgan E.F., Unnikrisnan G.U., Hussein A.I. (2018), depend on the ultrastructural organization of type I collagen fibrils filled with semicrystalline carbonized hydroxyapatite, and not on microscopic porosity (canals of Havers) [18, 19]. Kokot G., Makuch A., Skalski K. et al (2018) expressed an interesting hypothesis that the modulus of elasticity of bone at the tissue level and some other mechanical parameters are genetically determined and practically do not change with age or osteoporosis [20].

Thus, the biomechanical interaction (stress-strain state) of the bone tissue and the implant depends both on the structural parameters of the bone, determined by the age, health status, and genetic characteristics of the patient, and on the characteristics of the implant material, in particular, on its modulus of elasticity. Tensile strength in the bone tissue increases non-linearly with an increase in the thickness of the cortical layer, its mineral density, and with a decrease in the modulus of elasticity of the implant. The deformation capacity of the “bone-implant” biomechanical system increases with a decrease in the thickness and mineral saturation of the cortical layer and the modulus of elasticity of the implant [21, 22, 23]. The customized selection of the modulus of elasticity of the material for bone substitution for a specific patient should be carried out considering the anatomical location of the bone defect.

With the same parameters of native bone samples, the mechanical parameters differ significantly in different parts of the same bone, for example, the femur, and in different segments of the skeleton [24, 25]. The works of M.V. Gilev et al showed that mechanical impact on the bone areas of the tibial plateau, the distal epimetaphysis of the radius, and the articular surfaces of the calcaneus causes changes at all structural levels of its organization. Different in intensity and vector of application of the load forces, according to Wolf's law, form a unique chemical composition and the relationship of the elements of the protein matrix and mineral crystals in the composition of the bone. The microarchitectonics of the bone in a particular segment of the musculoskeletal system determines the nature of the fracture and the likelihood of a bone defect [26, 27].

It is recommended to use the following characteristics for designing and selecting bone substitutive materials: modulus of elasticity, pore size, tensile strength [28, 29, 30]. The porous structure of implants with gradient density allows the bone to grow into it. If the material with the structure gradient similar to human bone tissue is applied to provide mechanical properties close to bone parameters, the probability of successful osseointegration increases. This is due to a more intense mechanical effect of the gradient implant on the surrounding bone than the effect of a homogeneous material. At the same time, the mechanical stress in the “bone-gradient implant” system does not exceed the physiological values that occur in an intact bone. Under the conditions described above, the probability of occurrence of the stress shielding phenomenon at the junction of the material and bone is reduced, which contributes to the prevention of aseptic instability of the implant [31, 32].

CONCLUSIONS

1. Mechanical properties of bone tissue in the supra-acetabular region fluctuate in a small range of values.

2. In male patients, mechanical characteristics do not change significantly with age. In women, the value of elastic deformation increases significantly with age. The maximum tensile strength and modulus of elasticity in women of different ages did not show any changes.

3. In young and middle age, the bone tissue of men and women does not differ in mechanical properties. In older men, the bone tissue is stiffer; in elderly women, the bone restores its shape better after a load.

4. The bone tissue of the supra-acetabular area under compressive loads is capable of partial restoration of its shape after the load is removed. High porosity of the bone causes an irreversible change in its shape by layer-by-layer compaction and destruction of the microstructure without disintegration into separate fragments.

5. The established values of the modulus of elasticity, ultimate tensile strength and elastic deformation can serve as guidelines in the selection of the materials of bone replacement for bone defects in the supra-acetabular bone tissue in patients of different age groups.

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