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Analysis of Bone Tissue Mechanical Properties

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A B S T R A C T

This paper deals with the torsional moment depending on the angle of torsion of the compact bone in laboratory animals and humans. Based on the data from laboratory animals, obtained by measurement, the data on dependence of the torsional moment and the angle of torsion were assumed for humans. Measurements were carried out on four groups of compact bone in laboratory animals. One was the control group, and three other groups were treated by various vitamin D_3 metabolites. Equal measurements were performed in only one group of compact bone in humans, due to the impossibility to treat humans with vitamin D_3 metabolites. Functional relations between the angle of torsion and the torsional moment for all groups of animal body tissue were determined by measurements, and the results were used to assume the reaction of human compact bone tissue if treated by vitamin D_3 metabolites.

Key words: *vitamin D_3, biomechanics, torsional movement, bone, osseous tissue*

Introduction

Micromeasurement relationship between tension and deformation of bone tissue has already been extensively investigated[1–4]. Bone is considered to be a physical body, behaving according to the laws of physics and mechanics. Mechanical behavior of the bone in standard physical situations equals the mechanical behavior of an elastic body. This is a conclusion based on primarily mechanical characteristics of the skeleton, in which bone diseases are firstly manifested as mechanical shortcomings of the construction. The bond between structure and function of the bone is obvious[1–5].

Precise mechanical analysis of the osseous tissue from the mechanical stand-

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point is, therefore, a complex issue. The analysis is based primarily on the hardness of the material, the relationship between deformation and tension of the bone, etc. These are considered as the relationships between molecules and atoms, which in turn means that every deformation study and osseous tissue tension study surmises substantial knowledge of the physical characteristics of the bone. Exactly this is a problem, since it is widely known that the composition and the shape of the bone are changing throughout the life[3,6–9].

Therefore, the choice of an appropriate bone model is of greatest importance in the determination of relationships between deformation and tension, as well as of the so-called threshold status which characterizes the bone as a material of threshold constructions. The most important feature of a threshold construction material is that the minimum of mass has the maximum of hardness.

The elasticity of the compact bone, as well as the other physical characteristics of the bone, are changing according to the mineral content. This notion was the impulse to investigate the changes in the hardness of the osseous tissue during a programmed flow of vitamin D_3 and its metabolic products on laboratory animals that were treated by the metabolites in different combinations and doses prior to sacrifice. The investigation was inspired by the fact that vitamin D3 and its major metabolic product, 1,25-dyhydrooxycholecalciferol (1,25-$(OH)_2D_3$), as well as its second metabolic product, 24,25-dihydrocholecalciferol (24,25-$(OH)_2D_3$), are important for the metabolism of the bone, and its regeneration after fracturing.

The aim of the investigation was to determine the influence of the mineral composition of the bone on total rigidity of long bones. In this investigation, we used long bones of laboratory animals whose composition and shape are similar to the human long bones.

Material and Methods

Physical and chemical properties of the osseous tissue are changing. They are in concordance with loading circumstances – strength and direction of the force applied, etc. These properties depend on the part of the observed bone, in which the mode of the loading plays a very important role. Therefore, any attempt to simplify the procedure can substantially and completely alter the observed features.

Based on the hypothesis that osseous tissue of the long bones, whose cross-section is much smaller than their length, is transversely isotropic, we chose torsional loading for the experiment. The theoretical solution was aimed at isotropic torsion.

The other important problem that makes this investigation difficult is producing the artificial bone samples in defined dimensions, and making sure that the axes of samples are parallel to the fiber direction. With that purpose we investigated the dependency of the static moment of torsion, torsion angle, and geometrical significance for the bone of laboratory animals in the control group as well as in three experimental groups, treated by metabolic products of vitamin D_3. Equal investigations were to be performed on human osseous tissue, and afterwards, based on the determined relationship between torsion angle and torsion moment for all groups of osseous tissue of animals. It was projected to predict the properties of the human osseous tissue in the given situations of vitamin D_3 metabolites implementation.

The tibial bones of compared animal group were labeled I to IV, the group labeled V to VIII was treated by 1,25-dihydrocholecalciferol, the group labeled IX to XII with 24,25-dihydrocholecalciferol, while the group labeled XIII to XVI was treated by a combination of the two metabolic products of vitamin D_3. The duration of the experiment and time of the sacrifice of animals were equal in all groups.

The measurements were performed on five human tibial bones in order to establish the values of torsion moment and angles of torsion, as well as changes of torsional inertia moment, depending on the location of the studied cross-section. Since all human tibiae were macerated, it was only possible to compare dimensional properties of human and animal bones. Human bones were studied at room temperature (23°C). Bone temperature during the experiment was 4±0.2°C.

Since the industrial torsional devices with great measurement precision presented excessive financial demands, we constructed much simpler torsional devices. These have proved to be acceptable since expected changes of dependence between the torsional moment and the angle of torsion are acceptably significant in order to calculate the effect of vitamin D_3 metabolites on the toughness of the compact bone. The accuracy was between 0.5 and –0.5 degrees, which cannot be considered as an outstanding error due to the differences in the mechanical hardness during the change of the mineral composition of the bone.

We constructed two different measurement units – one small and one large – since we examined two different samples the dimensions of which did not allow the use of only one unit. We measured human tibiae (length 25 cm), and laboratory animals tibiae (length 6 cm).

It was not possible to perform the experiment on the human sample treated by different metabolites of vitamin D_3. Therefore, the experiment on human samples was performed only once, by means of the larger measurement unit.

The results of measurements on human and animal samples enabled us to determine the functional relationships between them. Based on this relationship, we simulated the behavior of the human tissue as if it were treated by the same metabolites as the osseous tissue of laboratory animals.

An original program was set up in Microsoft Visual Basic (Microsoft Corp., Seattle, WA, USA). All data from the experiment, as well as the other data, were interpolated by means of the program package Mathematica and stored in MS Access (Microsoft Corp., USA) database that was linked to the Visual Basic program, so every change was refreshed instantly.

Results

Hardness measurements were performed on five samples of macerated human tibiae that were bent until they fractured. The total diagram of the obtained results is shown in Figure 1, and it is only a comparative depiction of mechanical behavior of human tibiae in the conditions of torsional tension. The data suggest a relationship between the torsional moment and the angle of torsion.

It has been confirmed that the tension up to about 400 Nm can be considered to be linear, whereby when the tension exceeds 400 Nm, it becomes alinear. The fracture of the tibiae was observed in the range between 550 and 600 Nm, while the highest value of angle of torsion was between 11 and 14°.

Figure 2 shows the data obtained by measuring the relationships between different samples over time. It can be observed that the angle of torsion is a very changeable value that differs between samples. For the control group (I–IV) it

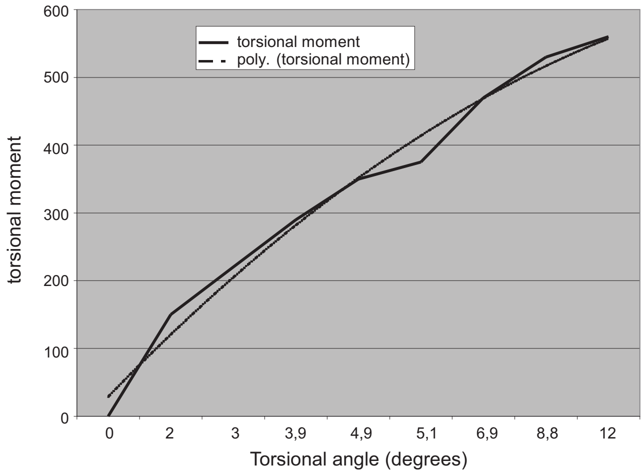

Fig. 1. Dependence of torsional moment and torsional angle on human compact bone.

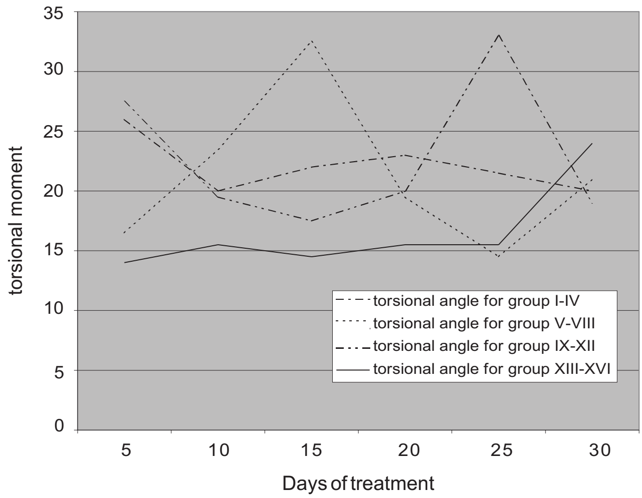

Fig. 2. Effect of time on torsional angle changes.

was 22.08°±2.245, for the first experimental group (V–VIII) 17.83°±3.116, for the second experimental group (IX–XII) 21.25°±6.669, while for the last experimental group (XIII–XVI) it was 23.083°± 5.928.

The measurement of torsional moment in relationship to time can be seen in figure 3. It is obvious that the group treated by 1,25-$(OH)_2D_3$ and 24,25-$(OH)_2D_3$ can withstand greater torsional moment when compared to other experimental groups.

The results in figure 4 represent the relationship of torsional hardness of the studied groups. The groups treated by 1,25-$(OH)_2D_3$ and 24,25-$(OH)_2D_3$ have higher hardness when compared to the

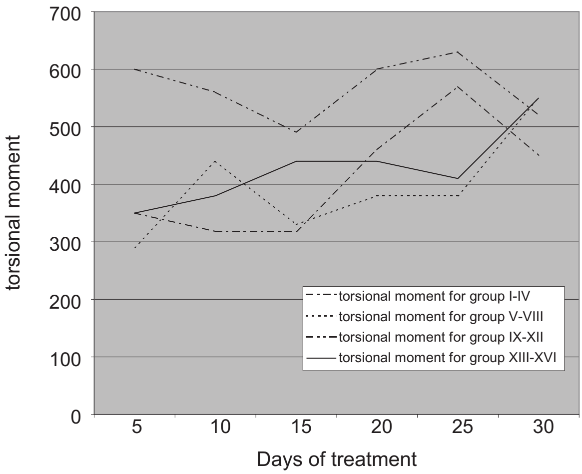

Fig. 3. Effect of time on torsional moment changes.

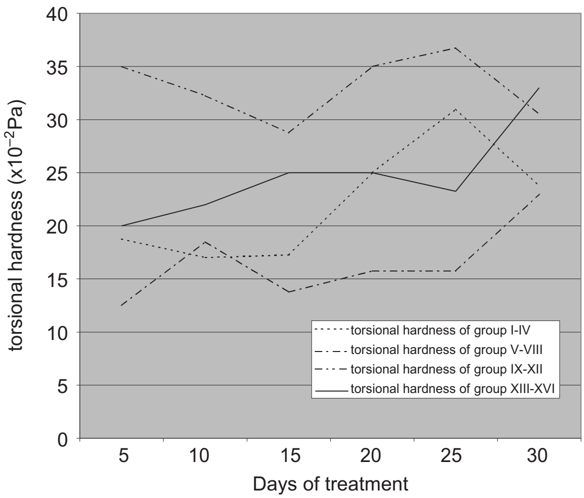

Fig. 4. Effect of time on torsional hardness.

control groups, but also when compared to other experimental groups.

Discussion and Conclusion

The relationship between bone structure and its function has not yet been established[2,3]. The osseous tissue is an entity that changes throughout life. This is especially related to module of elasticity changes of the compact bone, depending on the mineral composition of the bone. These changes are sudden and leap-like, so a mineral change of about 2 to 3% can result in module of elasticity changes to 60 to 100%. Changes of the module of elasticity result in changes of other physical values, and other physical properties as well. Therefore, in solving and determining the physical properties of biological materials one must include presumptions and simplifying procedures that cause substantial differences in computed and measured values[9–13].

Structural difference of osseous tissue compared to crystalline materials, whose deformation mechanism is explained by multiplication of dislocatory fields, is not acceptable in fibrous materials like bone. In order to discover a suitable model for explaning the mechanism of deformation development in osseous tissue Muftić[5,11] had considered an assumption that osteon fibers (cylindrical osseous units), connected one to another by osseous matrix, could be exhibiting two different types of deformations: elastic and plastic deformation phases. In the elastic phase there is an ongoing elongation of osteons and a relative returning movement which is allowed by the matrix. If the tissue returns to its initial size, the total movement is considered to be an »elastic« deformation. The phase of plastic deformation is characterized by the so-called ripping of the osteons out of the matrix, which results in the inability of the tissue to return to its initial size once the force has been removed. Therefore, permanent deformation develops[10–14].

It can be concluded that 400 Nm is the borderline for linear deformation, and that the deformation becomes nonlinear with the increase in force. The fracture threshold is 550 to 600 Nm, while the greatest angle of torsion is 11 to 14°.

The torsional angle for the studied groups differs greatly from that of the control group which is 20.56°. This could mean that the group treated by 1,25-$(OH)_2D_3$ and 24,25-$(OH)_2D_3$ can sustain a greater torsional moment, when compared to other experimental groups. It does not mean, however, that this group exhibits greater hardness than other groups, since this measurement has not taken into account the geometrical characteristics of the cross-section of the bones.

It can be, however, concluded, that the torsional angle of the groups treated by vitamin D_3 metabolic products significantly differs from the mean value of the control group.

The group treated by the combination of both metabolic products has greater hardness than the control group, as well as the other studied groups.

This experiment has undoubtedly proved that the torsional angle depending on the torsion moment can, with substanitial accuracy, determine the influence of vitamin D_3 on physical properties of the osseous tissue. This should encourage further studies of the influence of the mineral composition of the osseous tissue on physical properties of the said tissue. Such studies might point to crucial data for the human and veterinary medicine, but biomechanics as well.

Due to the small sample sizes it was not possible to establish the criteria for statistical significance, a fact that speaks in favor of extending the research in this field.

REFERENCES

1. COWIN, S. C.: Bone mechanics. (CSC Press, Boca Raton, New York, 1991). — 2. CURREY, J.D., K. BREAR, P. ZIOUPOS, J., Biomechanics, 29 (1996) 257. — 3. MUFTIĆ, O., Strojarstvo, 15 (1973) 74. — 4.FUNG, Y.C.: Stress-strain history relations of soft tissues in simple elongation. In: Biomechanics. Its foundations and objectives (Prentice-Hall, Englewood Cliffs, New York 1972). — 5. MUFTIĆ, O., D.

MILČIĆ, Sigurnost, 2 (1997) 67. — 6. SASSKI, N., N. MATSUSHIMA, T. IKAWA, A. FUKUDA, J. Biomechanics, 22 (1989) 157. — 7. VUKIČEVIĆ, S., Č. BAGI, G. VUJIČIĆ, B. KREMPIE, A. STAVLJENIĆ, M. HERAK, Bone and Mineral, 1 (1986) 383. — 8. KEROS, J., I. BAGIĆ, Ž. VERZAK, D. BUKOVIĆ Jr., O. LULIĆ-DUKIĆ, Coll. Antropol., 22 (1998) 195. — 9. MILČIĆ D., Analysis of mechanical properties of bone tissue based on its mucrostructure. M.Sc. Thesis (Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb 1997). — 10. MUFTIĆ O., D. MILČIĆ, J. SAUCHA, V. CAREK, Coll. Antropol. 24 Suppl. (2000) 97. — 11. JURČEVIĆ, T., O. MUFTIĆ, Coll. Antropol. 22 (1998) 585. — 12. MILČIĆ D., J. KEROS, J. SAUCHA, Z. RAJIĆ, R. PEZEROVIĆ-PANIJAN, Coll. Antropol. 24 Suppl (2000) 15. — 13. SHIGLY, J.E.: Mechanical Engineering Design (McGraw-Hill, New York, 1986). — 14. LOVASIĆ, I., T. ŠKARIĆ-JURIĆ, B. BUDISELIĆ, L. SZIROVICZA, Coll. Antropol, 22 (1998) 307.

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ANALIZA MEHANIČKIH SVOJSTAVA KOŠTANOG TKIVA

S A Ž E T A K

U radu je utvrđen suodnos momenta svijanja i kuta svijanja tkiva zbite kosti pokusnih životinja i čovjeka. Temeljem mjerenja utvrđenih podataka za pokusne životinje pretpostavljena je i zavisnost momenta svijanja za kost u čovjeka. Mjerenje je provedeno na četiri skupine tkiva zbite kosti pokusnih životinja. Pri tome su tri skupine životinja dobivale različite metabolite vitamina D_3, a četvrta je skupina bila kontrolna. Zbog nemogućnosti obrađivanja čovjeka metabolicima vitamina D_3, istovjetno je mjerenje provedeno samo na jednoj skupini tkiva zbite kosti čovjeka. Pri mjerenju su za sve skupine koštanig tkiva životinja utvrđene funkcionalne veze između kuta svijanja i momenta svijanja. Temeljem dobivenih rezultata predmijeva se kako bi se ponašala zbita kost u čovjeka tretiranog metaboliticima vitamina D_3.

Key words: vitamina D_3, biomehanika, moment svijanja, kost, koštano tkivo