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Evaluation of The Optical and Mechanical Properties of The Human Mandible

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Evaluation of The Optical and Mechanical Properties of The Human Mandible

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Abstract

Statement of the problem: It is important to understand the mechanical properties of the mandible that has nonhomogeneous structure.

Objective: The aim of this study is to determine the optical density, apparent density, modulus of elasticity and strength values of mandible in vitro and to evaluate their relations.

Materials & Methods: Specimens obtained from six cadaver human mandibles. The sample figure dimensions was set as 2.8 cm length, 1.2 cm width, 0.6 cm mid-section, 0.5 cm height. Optic density (OD) is evaluated with radiographs using an optic densitometer. Apparent density (AD) is determined by mercury overflow tests. Modulus of elasticity (E) and strength(S) is determined using strain gauges and mechanical press. Data evaluated with simple regression analyzes (SRA), multiple regression analyzes (MRA), fuzzy algorithm.

Results: Values were found to be 1.115-1.586 for OD, 1.08 g/cm^3-1.46 g/cm^3 for ADA, 0.6-16.5 GPa for E, and 4.74 MPa-23.93 MPa for S. Simple regression analyzes revealed reverse-geometric relationship between OD-AD, reverse-linear relationship between OD-S, and reverse-logarithmic relationship between OD-E. MRA results pointed to a reverse relation between S-E. Fuzzy model was found to have a higher prediction performance.

Conclusion: Mandible has a nonhomogeneous and anisotropic structure. Modulus of elasticity is controlled by many parameters such as the material porosity, physical density, mineral quality, and texture. By using fuzzy algorithm, more reliable results can be obtained particularly in making classifications involving uncertainty.

Keywords: Bone, Human Mandible, Density, Modulus of Elasticity, Strength.

Introduction

The human mandible has regional and anatomic differences and has a nonhomogeneous structure. Therefore, the mechanical properties as density, modulus of elasticity and strength of bone are critical aspects on the treatment plan, the surgical approach, healing time and progressive bone loading in oral implantology.[1] Modulus of elasticity and strength of bone can be determined directly through 3-dimensional models created by computer-assisted finite element analysis (FEA) in addition to the experimental methods.[2, 3] However, in FEA the bone is assumed to be homogeneous and isotropic and moreover for most of the 3-D models created the modulus of elasticity was set to a fixed value.[3, 4] With the current technology, it's impossible to determine the modulus of elasticity of bone in vivo.[3] Therefore, determining the modulus of elasticity and other mechanical properties in vitro and with a strong validation is an important research topic for dentistry. Researches, aimed to evaluate the mechanical properties of bone, were carried out on different bones.[5]

Determining the mechanical qualities of the bones and their reactions against different forces would contribute to diagnosing and treating bone-related diseases along with implant treatment procedures.

Materials & Methods

The present study was carried out between 1997-2000. Six human cadaver mandibles were obtained from Hacettepe and Ankara University, Anatomy Department Laboratories. After removal of the soft tissue and cleansing the specimens were processed.

Samples were prepared 2.8 cm in length, 1.2 cm in width, 0.6 cm in mid-section and 0.5 cm in height. Samples were cut with low-rotating electric handsaw (Autopsy saw, Stryker Co., USA) and steel fretsaw (Stilson, Ltd, Swiss) parallel with the basis by keeping the bone dry while cooling with water. They kept in zip-locked bags wrapped in wet gauzes at -20°C. 14 samples were obtained from six different mandibles.

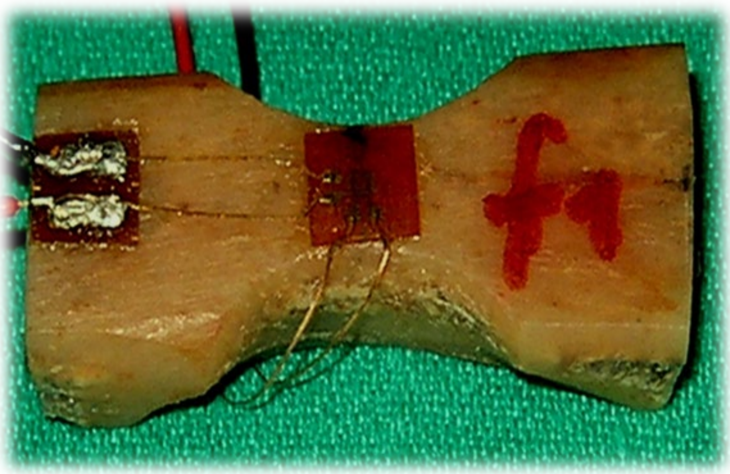
Radiographs were taken using periapical films (Cea Dent, E speed, Sweden) and X-ray unit (Trophy, Radiology Inc., France). Optic density analyses were made on each radiography with a certain standardization by using Orthochromatic Macbeth, TD-931 transmission densitometer (R. Y. Parry Ltd., USA).

For determining the apparent density the bone samples were left uncovered for 24 hours to be cleared of surface wetness and they were weighed on sensitive scale (Precisa 8200 D, Swiss). A glass petri box was weighed on the sensitive scale while empty. A godet was filled with mercury and placed inside the petri box. The sample immersed in mercury and overflowing mercury collected in the petri box weighed on the sensitive scale (Overflowing mercury + container). This procedure was repeated for all samples. The calculation of density for each sample was made in accordance with the formula:

$$\text{Density} = \frac{sampleweigh * specificweighofmercury}{(overflowingmercury + container) - conteinerweigh}$$

For determining the modulus of elasticity, a total of 14 WA-xx-030WT-120 strain gauges (Measurements Group Inc., Raleigh, USA) were attached on the samples with an adhesive (M-Bond 200, Measurements Group Inc., Raleigh, USA) as seen in Figure 1.

Figure 1. Bone sample-F 1 with strain gauge that attached terminals and soldered wire connections.



Resistance wires were tied to the terminals to provide connection between strain gauges along with terminals and data recorders. Before the recordings, strain gauges and the wires were checked with an ohmmeter (Sanwa Elec. Ins. Co., Japan). Bone sample was placed into the mechanic press, under fixed loading and at certain loading levels, vertical and horizontal unit deformations were recorded from the channels into which strain gauges had been tied. Then vertical loading values were seen on the indicator located on the press. At least 10 data-recordings were performed for each sample until it broke. The modulus of elasticity for each sample was calculated as the comparison of stress over the strain in accordance with the curve of line. Bone sample located in the press subjected to force until it broke. And loading values for each sample were recorded at the moments of fracture. Compressive strength values were determined as ratio of loading force to the cross section.

Results

Obtained measurement values of the study could be seen in Table 1.

Table 1. Mean optical density (OD), apparent density (AD), modulus of elasticity (E) and strength (S) values obtained from bone samples as a result of experiments.

Sample no	Optical density	Apparent density (g/cm3)	Modulus of elasticity (GPa)	Strength (MPa)
A1	1,115	1,24	9,3	15,00
A2	1,147	1,36	11,7	17,27
B1	1,256	1,22	2,5	12,38
B2	1,387	1,08	2,5	5,65
C1	1,115	1,45	5,4	14,78
C2	1,526	1,27	8,6	8,33
D1	1,143	1,33	4,4	19,43
E1	1,339	1,26	0,6	7,17
E2	1,227	1,46	5,2	17,37
E3	1,340	1,12	2,7	4,74
F1	1,569	1,19	16,5	23,93
F2	1,586	1,14	2,1	2,68
F3	1,472	1,18	7,8	5,24
F4	1,580	1,25	1,8	9,97

Relations between the parameters were evaluated by simple and multiple regression analyses and fuzzy algorithm.

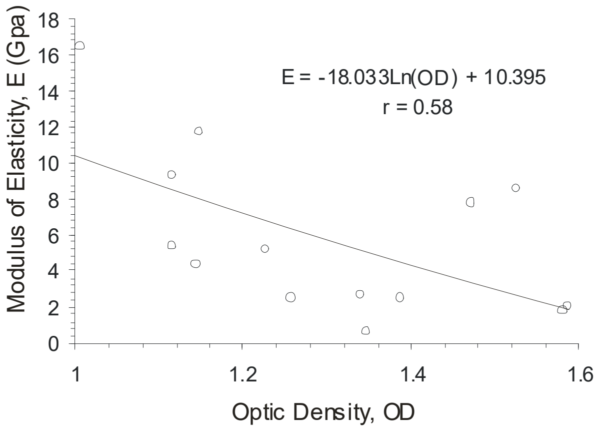
In these analyses, crosswise correlation co-efficient, and average Root Mean Square Error (RMSE) indexes were calculated.

Linear, exponential, power-related and logarithmic functions were applied for each simple regression analysis. F-test results and regression co-efficient were determined. Whereas a geometric-reverse relation between optic density and apparent density was observed (regression co-efficient 0.54), the relation between optic density and strength was linear-reverse with a regression co-efficient of 0.84, and a reverse logarithmic relation was found between modulus of elasticity and optic density with a regression co-efficient of 0.58 value (Table 2, Figure 2).

Table 2. According to the simple regression analysis, the functions obtained with the modulus of elasticity being the dependent variable (D: Degree of free, F: F value, Sigf: Safety Space)

Dependent variable	function	r²	Df	F	Sign	b0 coefficient	b1 coefficient
E	linear	.302	12	5.19	.042	22.9058	-13.130
E	logarithmic	.338	12	6.11	.029	10.395	-18.033
E	power	.267	12	4.37	.059	9.4644	-3.1644
E	exponential	.243	12	3.85	.073	87.2297	-2.3236

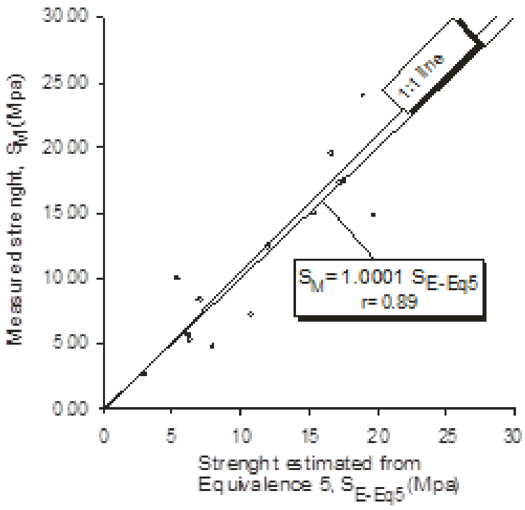
Figure 2. Relation between optic density and modulus of elasticity based on simple regression analysis.



It was seen that the most significant relationship according to the RMSE index was the equation showing the relationship between optical density and density.

Five multilateral regression equivalences were created: Equation 1 (Eq1), Equation 2 (Eq2), Equation 3 (Eq3), Equation 4 (Eq4) and Equation 5 (Eq5). First four equations were used for the estimation of the elasticity modulus and the fifth one was developed for strength. Eq5 had the highest coefficient in cross-correlation however could not show the same performance in RMSE index as it can be seen in Figure 3.

Figure 3. Measured and estimated values of modulus of elasticity according to Equivalence 5 based on multiple regression analyzes.



The cross-correlation coefficients of Eq1 r=0.67 and Eq4 r=0.67 were higher than the Eq2 (r=0.63), and Eq3 (r=0.54). RMSE values of the Eq3 were slightly lower than the others, which pointed to the higher performance of Eq3. Developed for strength, Eq5, on the other hand, gave the highest coefficient in cross-correlation, but did not show the same performance in RMSE index.

The fuzzy model created in this study takes optical density and density as input parameters and gives the modulus of elasticity as the output parameter. Optical density was expressed with five fuzzy sets whereas density with four. The modulus of elasticity was determined with five fuzzy sets. With these data sets, a total of 20 'if-then' rules were written and the Mamdani Model was used for the estimation of the modulus of elasticity values. After running the fuzzy model, 14 modulus of elasticity were estimated. The fuzzy model had a higher regression coefficient (0.75) than Eq3 (0.54) had the same parameters as independent variables. Therefore, the fuzzy model had a higher estimation performance.

Discussion

Compared to the other bones of the skeleton system, mandibular bone has a complex structure and function with a unique position. Although the issue is of current interest, in vitro mechanical studies on mandibular bone are limited.[6] Therefore, difficulties were experienced both in the selection and implementation of methods and procedures to be employed in the study.

In this study, densitometric analysis was preferred for it is an easy, low radiating, and sensitive method which can present numeric data about the density of the bone.[7] However, today, quantitative computed tomography can also be used as a very accessible and reliable method in this respect.[8, 9] Apparent density is an important parameter defining the quality of the material. Misch et al[1] used the term "density" for the volume-weight ratio by weighing via sensitive scale cylindrical samples belonging to fresh frozen human mandible and by determining volumes through the calculation of sample diameter and length.[1] Rho and Ashman[2] used two definitions as structural and material density belonging to samples made of human bone and bovine cylindrical samples. For structural density, they defined the ratio of sample weight to its volume. And for material density, they calculated the ratio of the amount of water overflowed by the bone samples to the specific weight of the water.[10] For determining apparent density, mercury overflowing method was used in this study. Since the modulus of elasticity cannot be determined in vivo, this research was carried out in vitro conditions.

In the literature, it is seen that strain-gauges were used to determine the elasticity modulus and strength values of the bone in vitro.[11,12] Giesen et al[13] determined the modulus of elasticity and apparent density of samples taken from human cadaver condyles by using strain gauges. In the groups where vertical and horizontal loadings were performed, the modulus of elasticity was proportionate with the apparent density and displayed a power-related relation. Moreover, in vertically loaded samples the modulus of elasticity values were higher compared to that of those loaded horizontally.

These mechanical properties can also be determined in vitro by the finite elements analysis method (FEA). Although the FEA studies have increased in recent years, it is stated that there are deficiencies in their accuracy.[14] There are numerous researches that employed FEA in which the effects of bone parameters on peri-implant stress/strain distributions have been studied. The validity of the simulations depends on morphology, material properties, boundary conditions and the bone-implant interface.[14]

Recently, some papers drew attention for the verifiability of studies with FEA. This includes questions about the limitations of FEA and highlights the value of validating data from FEA modeling and experimental data. Morgan et al[4] stated that modulus of elasticity values, set by finite element models were significantly higher than those set by experimental method values obtained from different anatomic parts of human cadaver bones. Van der Linden et al[6] stated that in determining mechanical qualities of trabecular bone samples, FEA were used in addition to experimental studies. They emphasized that these models had fully represented 3-dimension structure but ignored differences related to material qualities of the bone. According to the FEA, bone is regarded as uniform, isotropic, elastic, and linear. However, researchers argued that the bone showed linear attitudes for small deformations but is not isotropic and uniform.[6] As pointed out, studies in which the bone is modelled through FEA method, the qualities of bone such as its being isotropic but not homogenous are ignored. Based on this argument one can state that models created with this method did not reflect the mechanical qualities of trabecular structure.[15]

Both vertical and horizontal strain were measured in the presented study. It was concluded that cross-sections picked in this direction would not lead to errors. The ratio of tension which was vertical to loading was calculated. This is known as ‘Poisson ratio’. These values were included while checking measurements of the modulus of elasticity.

These studies show that trabecular bone poses behaviors similar to materials, which are issues for engineering, because of its cell structure and ability to absorb energy. But a striking point seen from these studies was the dramatic variety for modulus of elasticity and strength values between different studies. These differences might be caused by several reasons of which the most important one is the anatomical difference and function of the tested bone. Findings from these studies support the mainly accepted hypothesis "function affects bone structure and resistance directly " known also as the "Wolff Law".[12,16]

Zyset et al[17] stated that modulus of elasticity of trabecular bone values between 1.3-14.8 GPa. This difference rested mainly on anatomical and individual differences and experimental technique. Misch et al[1] found the modulus of elasticity belonging to mandible as about 96.2 MPa with 24.9-240 MPa in the existence of cortical plates.

The bone morphologies and Young’s modulus of cortical bone and cancellous bone in human mandibles vary greatly across individuals and sites.[18] In previous FEAs, Young’s modulus was assumed to be 0.231 to 1.10 GPa for low-density cancellous bone and 1.37 to 9.5 GPa for high-density cancellous bone.[18,19]

In this study, modulus of elasticity values of mandibular bone were 0.6-16.5 GPa whereas compressive strength values were 2.68-23.93 MPa.

One of the other limitations of FEA is that the models did not accurately reproduce the complex forces that are exerted during chewing.[20]

A literature review of FEA studies of dental implants with their model validation process was performed to establish the criteria for evaluating validation methods with respect to their similarity to biological behavior. The articles were categorized according to their validation method. Validation techniques with a high level of sufficiency and efficiency are still rare in FEA studies on dental implants. High-level validation, especially using in vivo experiments tied to an accurate finite element method, needs to become an established part of FEA studies.[21]

Fuzzy algorithm is a very reliable method especially for classification systems. This theory has been used for many medical systems. Fuzzy logic is a highly applicable method in the development of systems based on evidence in medicine. It is used in diagnosis, optimal diagnosis of medical treatments, and monitoring of patient data.[22, 23]

Recently, in the literature, it is seen that more papers on the subject have increased, and studies are mostly concentrated in the field of radiology and diagnosis. In this study, with the fuzzy algorithm, by determining both the localization, length and diameter of the implants and the characterization of the load-bearing capacity of the bone, faster and easier diagnosis and treatment planning can be made in oral implantology based on radiological examinations.

Conclusion

It is understood that the value of the mechanical properties of mandible are not stable and vary depending on methods, conditions along with regional and personal differences. Thus, considering bone do not have a homogenous and isotropic structure, setting modulus of elasticity of the bone as a constant as in FEA which is an updated research method in oral implantology, might be misleading. The elasticity modulus of solid materials of all kinds including bones is controlled by many parameters such as the porosity, physical density, mineral qualities and tissue. As we know it is impossible to determine the modulus of elasticity of the bone in vital conditions, assumption of this parameter could be made by densitometric analyses or more reliable methods as CBCT.

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