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NONINVASIVE METHOD FOR DETERMINING THE PHYSICAL AND MECHANICAL CHARACTERISTICS OF PATIENTS BIOLOGICAL TISSUES

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Abstract

Morphological and biomechanical structure features of organs and tissues of the maxilla-facial area play the decisive role in the development of pathological processes and diseases. Understanding of their mutual influence while functioning and damage is one of the main points for a correct diagnosis, adequate treatment planning and rehabilitation. The multicriteriality of dental patients following-up, requires a doctor's knowledge of scientific and technical disciplines, such as strength of materials, theory of elasticity, theory of plasticity and creep, theoretical mechanics, etc. In medical universities, the principles of these disciplines, as a rule, are studied for one or two weeks, and are often combined within a single discipline - physics. At the same time, everywhere, medical and preventive treatment facilities are equipped by sophisticated diagnostic equipment, the most common representatives of which are the cone-beam computerized tomography scanners. If the clinical manifestations of the norm, injury, disease and rehabilitation, defined on computer visualizations, are studied by students and practitioners in a full measure, the biomechanical changes, inherent for these processes, are estimated less frequently. This leads to the fact, that occlusive component is not properly taken into consideration in the pathogenic mechanism. The absence of biomechanical aspect in the assessment of the pathology prevents the systemic strategy construction of biomechanical models of functional recovery and socialization. The paper presents the algorithm of conversion of radiological density of biological tissues, assessed on the basis of computer visualizations, measured in Haunsfield units (HU), to real density, defined as the ratio of the object mass to the volume, occupied by this object. Based upon computed tomography, the thresholds of density and number of mechanical properties of maxilla-facial area tissues were calculated; and that provide the possibility of biomechanical modeling at the stage of treatment planning and evaluation of disease development dynamics, as well as the rehabilitation of patients.

Keywords: Radiological density, real density, computed tomography, biomechanics, rehabilitation.

Introduction

Finding the ways for treatment optimization, necessitate the close cooperation of dentists, having various specialties; at that, biomechanical feasibility is the platform, upon which team approach to functional recovery and social optimum is formed [1]. Ignoring of biomechanical aspect have additional element of uncertainty for the treatment of patient, because in different situations, stress can act as a factor, contributing to the rehabilitation, or as the factor leading to additional damage of tissues, bearing load [2].The complexity of biomechanical tasks is due to the variety of physical, chemical characteristics and complicated geometry of the restored organs and tissues. The high level of anisotropy of biophysical characteristics of the regenerative materials, in relation to the characteristics of organs and tissues, puts in doubt the benign outcome of the treatment [3, 4]. At present, the prediction of state of the cyclically loaded dentoalveolar area, and the defining of margin safety of reconstruction and its lifetime, are not regulated, despite the obvious importance of this task. The main reason, explaining the lack of prediction of reconstructions states, is a significant number of variables, which affect the dynamics of changes from elastic deformations to plastic deformations [5]. For increasing the lifetime of reconstruction, it is necessary to determine the mechanical properties of biological tissue area, where the functional recovery element would be installed. In case of elastic deformations of the system "biological tissue - restoring element" the possibility of occlusion damage of tissue depends on the ratio of mechanical characteristics of the element material and the section of biological tissue – the less is this ratio, the lower is the possibility of tissue destruction by the work of restoring element [6]. In this case, biomechanical analysis, using modern methods of mathematical modeling, allows to explore more deeply the work of any biosystem, as in normal condition, as in case of its reconstruction. [7] The problems of modeling are still relevant during the planning of dental treatment, the evaluation of received results, the prediction and monitoring over the dynamics of rehabilitation [8, 9]. It is known, that one of the key parameters, necessary for describing the biomechanics of the system “restorable tissue - restoring fragment” is the tensile strength and Young's modulus. The defining of these values makes it possible to come to the computer modeling, allowing to get rid of the full-sized or bench-scale researches and in a fairly short period of time, to optimize the logic of the approach to the treatment of this patient [10, 11, 12]. Both existing and future needs of computer simulation development provide the creation of database, oriented to the understanding by dentists and designers of medical equipment, the need of minimization in computer models the anisotropy of biomechanical characteristics of restorable tissues and restoring elements, with maximum approximation to the *status localis* of the particular patient.

Research Objective

To provide the method of calibration of Hounsfield units (HU) to the real density of biological tissues (g/cm^3), that allows to obtain the main mechanical characteristics of patient's biological tissues, actually in real time.

Materials and Methods

The basis of biomechanical modeling of reconstruction elements is the condition of strength or similar condition of rigidity, which are combined: load – the characteristics of biological tissues and characteristics of restoring materials – simulation model (the construction) of the analyzed element. Presenting these conditions in the form of triangle, it is possible to define any of the triangle vertices with the known values of two others. The accuracy of the obtaining results and their compliance to the *status localis* of the particular patient, depends on the accuracy of main defined mechanical characteristics - the modulus of elasticity and tensile strength.

For biomechanical modeling of disease occurrence, its development and the achievement of rehabilitation, it is necessary to create analytical dependences between the radiological density of biological tissues HU, their physical density (ρ) and mechanical properties - tensile strength (σ) and modulus of elasticity (E), by creating a linear dependence between the numbers of HU, measured in the negative and positive ranges, and physical density ρ, with the definition of the correlation between the unit of HU and the increment of physical density, that allows to obtain the main mechanical characteristics of patient's biological tissues, on the basis of computed tomography data.

Description of the method. In known technical solutions, using interactive software packages (MIMICS, Ez3D and others) the measurement of radiological density of biological tissues allows to define the conformity of gray color tomography values to the gray color values on the monitor. The values of grey color on the visualizations are expressed accordingly to the Hounsfield scale. This scale corresponds to 256 values of gray color on the monitor.

Since the scale consists of 4095 values of Hounsfield units, including: air HU = - 1,024; water HU = 0; then assuming for air $\rho = 0.00129$ g/cm^3 and for water $\rho = 1.0$ g/cm^3, we found that the unit HU1 correspond to density $\rho=0.975 \cdot 10^{3}$ g/cm^3. Further, conventionally combining the beginning of the scale with a mark HU = -1024, you can get the absolute increment of ΔHU numbers for the investigated objects.

Technically setting problem is solved as follows: after carrying out the procedure of computed tomography and receiving on the screen of monitor the reconstructed image, the tool bar "measurement of density between two points" is activated in necessary box, then the cross-section is made by the cursor; the value of radiographic density is determined at the particular point of tissue. Then, using the obtained value of radiographic density and defined dependence, the value of physical density of tissues in particular anatomical area is received [13]. The number of measurements significantly raises the estimation accuracy of *status localis* of the investigated tissue.

The example of calculations. Suppose the patient's area, planned for the installation of the implant, has the minimum value of density in Hounsfield units = 148, the maximum = 1988.

The calculation formula $\rho=1.29\cdot10^{-3}+0.975\cdot10^{-3}\cdot\Delta HU$ g/cm^3.

The minimum value of the bone density in the physical density units at HU = 148, is calculated by the formula and is equal to 1.143 g/cm^3, as far as

ρ min = $0.975\cdot10^{-3}\cdot\Delta HU+1.29\cdot10^{-3}=1.143$ g/cm^3, where $\Delta HU = 1024 + 148 = 1172$.

The maximum value of the bone density in the physical density units at HU = 1988, is calculated by the formula and is equal to 2.94 g/cm^3, as far as

ρ max = $0.975\cdot10^{-3}\cdot\Delta HU+1.29\cdot10^{-3}=2.94$ g/cm^3, where $\Delta HU = 1024 + 1988 = 3012$.

Consequently, the average value of bone density in the area of planned implant insertion.

(ρ min + ρ max):2 = (1.143 g/cm^3 + 2.94 g/cm^3): 2 = 2.041 g/cm^3

In the process of developing and estimation the density thresholds of biological tissues, 334 tomograms of men and women, under the age of 60 and 136 tomograms of dental patients, under the age of 16, were taken for the research. On the basis of data on radiological density of biological tissues, using the revealed dependence: $\rho = 1.29\cdot10^{-3}+0.975\cdot10^{-3}\cdot\Delta HU$ g/cm^3, between the radiological density and the real density of biological tissues of human being, the thresholds of real density for biological tissues of human being were determined (Table 1).

Table 1 – The correlation of radiological density (HU) and real density thresholds (g/cm^3) of biological tissues.

Tissues		Radiological density	Real density
Bone tissue	Adult Child	226…3071	1.2200…3.9939
Enamel	Adult	1553…2850	2.5139…3.7784
	Child	2042…3071	2.9906…3.9939
Compact layer	Adult	662…1988	1.6451…2.9380
	Child	586…2198	1.5710…3.1427

Spongeous bone	Adult	148…661	1.1440…1.6442
	Child	156…661	1.1518...1.6442
Muscular tissue	Adult	-5…135	0.9948…1.1313
	Child	-25…139	0.9753…1.1352
Adipose tissue	Adult	-205…-51	0.7998…0.9500
	Child	212…-72	0.7930…0.9295
Skin	Adult	-718…-177	0.2996…0.8271
	Child	-766…-202	0.2528…0.8027

Applying of defined dependence between the radiological density and real density of biological tissues, it is possible to determine the thresholds of the modulus of elasticity and tensile strength of biological tissues. To solve this problem, we used the empirical formula [14].

$$E=2195\,\rho^3 \text{ and } \sigma=60\,\rho^2,$$

where E - modulus of elasticity, σ - tensile strength - the mechanical stress, above which there is a destruction of the material, ρ - real density of the biological tissue.

Table 2 shows the values of mechanical characteristics of human biological tissues in the range of HU numbers, calculated according to the formulas given above.

Table 2 - The dependence of HU numbers and mechanical characteristics for hard and soft tissues

Tissues		Tensile strength (MPa)	Young's modulus of elasticity (hPa).
Bone tissue	Adult Child	89.30…957.07	3.97…139.84
Enamel	Adult	378…856	34.7…118.36
	Child	537.59…957.07	58.71…139.84
Compact layer	Adult	162…518.6	9.75…55.77
	Child	148.08…592.59	8.51…68.13
Spongeous bone	Adult	78.4…161.97	3.28…9.73
	Child	79.60…162.20	3.35…9.76
Muscular tissue	Adult	59.16…76.6	2.15…3.17
	Child	57.07…77.32	2.04…3.21
Adipose tissue	Adult	38.21…54.04	1.11…1.88
	Child	37.73…51.84	1.09…1.76
Skin	Adult	5.36…40.94	0.059…1.24
	Child	3.83…38.66	0.035…1.14

Comparing the results, shown in Table 2 with data from the work [15] the correlation is visible, where the strength of spongeous bone varies in the range of 26-160 MPa, the strength of compact bone varies in the range of 50-400 MPa and the values of elasticity moduli of spongeous and compact bones are equal to $5.0 \cdot 10^3$ MPa and $20.0 \cdot 10^3$ MPa, respectively. It is to be supposed, that after the verifying of given empirical formulas, their differentiation by sex and age of the patients, the results for determining the mechanical characteristics will be more accurate.

Discussion

In technology, there is a fairly strict separation of invasive and noninvasive methods for determining the physical and mechanical properties of materials. In the process of determining the mechanical properties of materials, as a rule, the invasive tests are carried out, using specially prepared samples and this method gives the most accurate results. Noninvasive methods of testing are less accurate; they are used for checking the quality of already finished products, whose materials properties are already known.

In medicine, according to the Nuremberg Code (1947), which established ethical principles for the researches, the preference is given to noninvasive testing methods. It is for this reason, certain problems come up with the definition of mechanical properties of patient's biological tissues. Increasing the accuracy of noninvasive approach to the determination of mechanical characteristics of hard and soft tissue of human being, we have developed the method for determining the density of biological tissues, based on computed tomography data.

Developed method allows to take into account both the geometric peculiarities and mechanical characteristics of organs and tissues, that allows to simulate all the elements of reconstruction, without opening the pre-operative area. Provided correlation of computed tomography data - the thresholds of radiographic density of biological tissues with the thresholds of real density, as well as basic mechanical properties of biological tissues, has an approximate nature, because the biological systems are not linear models, by definition. For example, the elasticity modulus reflects strictly elastic (linear) properties of tissues. Therefore, when analyzing the linear model, which is more rigid system, than the biological system, it should be taken into account, that obtained moving will be less, and the stress will be as greater as entered mechanical properties vary from real ones. On this basis, detrimental stresses, obtained by calculation, and formed under the influence of occlusive load, would be different. Converse statement is also true. The reaction of the body to the injury, with a complex system of homeostasis saving, does not allow to carry over data, obtained by calculation, to the conditions of the problem, described by mathematician. Conceptually, the set of specific data, implies the choice of certain biophysical (mathematically structured) model of biological tissue for describing its macroscopic properties. However, the suggested ratio of biophysical and mechanical characteristics can be concretized in the process of implementation of proposed method by clinicians, and have differentiated nature, depending on the solving task.

Conclusion

The developed method for calibration of Hounsfield units to real density, allows us to study the change of physical and mechanical properties of the patient's biological tissues while their loading and interacting with restoring elements, when planning of patient's treatment and during the rehabilitation period, upon condition of declaration of physical and mechanical properties of the restoring material by the manufacturers.

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