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O. V. Pogrebnoy

BIOMECHANICAL MODELING OF ELASTIC PROPERTIES OF BONE TISSUE

An original method for studying the morphometric characteristics of spongy bone tissue was proposed. Using this method the distribution of the density of the spongy bone tissue of the distal metaepiphysis of the radius was studied. A decrease in the content of spongy bone tissue along the longitudinal axis of the bone has been experimentally proved. Modeling the mechanical properties of spongy bone tissue, according to the known versions of models for the elastic modulus of discontinuous media, makes it possible to calculate the behavior of bone tissue in conditions of various types of interaction. The comparison of the elastic moduli obtained according to our data with the results of other researchers has shown their comparability.

Keywords: *radius bone; spongy bone tissue; elastic modulus; fracture; section.*

Introduction. Fractures of the distal epiphysis of the radial bone are the most common injuries to the wrist joint and involve the articular surfaces of the distal radial and wrist joints in 50–55 % of cases [16]. At the same time, there is an obvious tendency to an increase in the number of cases of injuries under consideration among patients over 50 years old, especially women [2]. One of the predisposing factors for the increase in the frequency of fractures in old age is osteoporosis.

Osteoporosis is a metabolic bone disease characterized by a decrease in bone mass and microstructural remodeling of bone tissue, which results in decreased bone strength and increased risk of fractures. Bone loss occurs gradually and is often diagnosed only after fractures. As women live longer, their risk of developing osteoporosis and fractures increases. Every 2nd woman and every 8th man over 50 years have such a fracture. After menopause, women have a maximum bone loss rate of 2–5% per year. As a result, a woman by the age of 70 loses from 30 to 50 % of her bone mass. For men, these losses range from 15 to 30 % [6].

The most frequent localization of osteoporetic changes and, therefore, fractures are the vertebrae (compression fracture of the vertebral body), the femoral neck and distal radius (Colles' fracture), (Fig. 1) [13]. Bone strength reflects the integration of two main characteristics: bone mineral density (bone mass) and bone quality (architectonics, metabolism, mineralization) [8].

The problem of studying mechanical characteristics, identifying morphological features of the bone structure and the frequent damage associated

with biomechanical features in this area are of practical interest. Methods of medical morphometry provide significant opportunities for the study of biological objects with a complex heterogeneous structure [3, 7, 11, 19]. In the diagnosis of osteoporotic changes, quantitative computed tomography (QCT) is also used. The advantages of this method are: the ability to determine the trabecular and cortical bones separately; faculty of 3D bone research; the QCT method allows to avoid various superpositions of the surrounding tissues [12, 20].

The aim of the work is to study the density distribution in the region of the distal metaepiphysis of the radius, in the area most often subjected to fractures during the development of osteoporotic changes. Based on the experimental data obtained, perform biomechanical modeling of the elastic constants of bone tissue.

Material and methods. Experimental studies were carried out on a preparation of the radius prepared according to the following method [10, 14]. The preparation was decalcified in 7.5 % aqueous solution of nitric acid for 10 days. The swelling of fibrous structures was eliminated by additional fixation in 96 % alcohol for period of 24 hours. Then the preparation was embedded in paraffin and sections were prepared using a microtome, ranging from the proximal pole to the distal, in the frontal plane, 12–14 μm thick. Histological sections were fixed onto glass slides and stained with hematoxylin-eosin in a standard manner.

The position of the rectangular coordinate system $Oxyz$ was chosen so that the xOy plane was parallel to the horizontal plane, and the apex of the radial styloid process was located on it (Fig. 2).

Fig. 1 – Frequent fracture localization

Fig. 2 – Position of coordinate system

Sections were photographed using a LEICA DMLS light microscope at $\times 100$ magnification and a CANON EOS M42 D30 digital camera. In this case, all structures of the spongy substance (central and peripheral zones) were necessarily included. The resulting digital photographs were transferred to a personal computer in the form of data files.

The images of section № 031, presented in Fig. 3, were obtained immediately after photographing (Fig. 3 a), and after completing the necessary preparation for conducting morphometric analysis on computer (Fig. 3 b). It

is obvious that the halftones and impurities presented in the original image should not introduce errors into the results of computer processing.

Fig. 3 - Fragment of the image of the section № 031:
a) after photographing; b) after preparation for morphometric analysis

To carry out morphometric analysis of images, a computer program has been developed in the object-oriented visual programming system Delphi. First, color photographs of bone tissue were transformed into black-and-white images, where cortical and spongy bone tissue corresponded to black, and intercellular space corresponded to white. In this case, it is necessary to achieve the absence of gray color, which introduces interference. For this purpose, a discrimination threshold was selected for each image. When scanning an image, pixels that exceeded this threshold were considered white, the rest of the pixels were considered black.

At the next stage of morphometric analysis, the number of black and white pixels for the processed image as a whole and for its individual fragments was calculated, which made it possible to determine the specific area occupied by the bone tissue, both for the entire section and for its selected parts.

The results of image processing of sections № 031, № 032, № 036, № 038 and № 040 are summarized in Table 1. The specific area P of the spongy bone tissue of individual cut fragments containing its representative areas was calculated. The obtained values were averaged.

Table 1 - Specific density of spongy tissue of radial sections

Numbers of sections	№ 031	№ 032	№ 036	№ 038	№ 040
1	0.2308	0.2145	0.1985	0.1516	0.1419
2	0.2165	0.2261	—	0.2665	0.1275
3	0.2387	—	—	0.2024	0.1315
4	—	—	—	0.1555	—
Average P	0.2287	0.2203	0.1985	0.1940	0.1336

According to the results of morphometric analysis in Fig. 4 a, graph of the distribution of the specific density of spongy tissue is plotted depending on the distance from the carpal articular surface. Specific gravity refers to the relative area of spongy tissue in sections. The abscissa shows the distance in millimeters from the carpal articular surface (direction of the z axis in Fig. 2), and the ordinate shows the specific density of spongy tissue P .

Fig. 4 - Distribution of the specific density of spongy tissue:
a) distribution of the specific density of spongy tissue P ;
b) distribution of discontinuity Θ

Discontinuity Θ is related to the specific density P of spongy tissue as follows: $\Theta = 1 - P$. The dependence of $P - z$ in the Θ and z axes is shown in Fig. 4 b. The curves in this figure represent the result of the least squares fit of the experimental data by a polynomial of the third degree.

Modeling the elastic properties of spongy tissue. The study of the effect of porosity on the elastic properties of bodies has been the subject of many experimental and theoretical works. For materials with Poisson's ratio $\mu = 0.25$, the dependence of the relative modulus of elasticity E on porosity has the form [5]:

$$E/E_0 = 1 - 1.96 \Theta + 0.96 \Theta^2, \quad (1)$$

where E_0 is the modulus of elasticity of the non-porous material.

As applied to heterogeneous systems, the formula for the relative modulus E is written as follows [17]:

$$E/E_0 = \frac{1 - \Theta}{1 + K_1 \Theta}, \quad (2)$$

where $K_1 \approx 1$ for materials with $\mu = 0.25$.

Let us apply formulas (1) and (2) to determine the relative modulus of elasticity E/E_0 of spongy tissue, using the experimental data Θ , recalculating P from Table 1 as follows: $\Theta = 1 - P$. The calculation results are summarized in Table 2.

The differences in calculation results are significant, ranging from 54 % for section № 031 to 69 % for section № 040.

The value of the elastic modulus E of spongy tissue, given in [1] without indicating the value of discontinuity Θ , is 200 MPa. It also shows the value of E_0 for cortical tissue, which is 18700 MPa. The value of the relative elastic

modulus E/E_0 , defined as the ratio 200/18700, corresponds to the discontinuity value $\Theta = 0.9132$ according to formula (1), and $\Theta = 0.9788$ according to formula (2).

Table 2 - Results of calculating the relative modulus of elasticity E/E_0

	Numbers of sections	№ 031	№ 032	№ 036	№ 038	№ 040
1	Discontinuity Θ	0.7713	0.7797	0.8015	0.8060	0.8664
2	E/E_0 according to (1)	0.0593	0.0554	0.0458	0.0499	0.0225
3	E/E_0 according to (2)	0.1290	0.1238	0.1102	0.1074	0.0716

The modulus of elasticity of the spongy tissue of the radial head was determined by the method of indentation of the indenter [9]. It was found that the required value of the elastic modulus does not exceed 40 MPa. Similarly, calculating Θ through the known value $E/E_0 = 40/18700$ using formulas (1) and (2), we obtain 0.9692 and 0.9957, respectively.

The range of changes in the values of the modulus of elasticity during compression of the wet cancellous tissue of the epiphyses of long tubular bones, obtained by different authors, is 26 ÷ 600 MPa, [15, 18]. Calculating the discontinuity Θ through the specified values of E/E_0 for the boundaries of the specified range, we obtain 0.9974 and 0.9972 for the left boundary by formulas (1) and (2), respectively, and 0.8368, 0.9378 for the right boundary of the range, by formulas (1) and (2), respectively.

It follows from the above data that the discontinuity value Θ , calculated for the maximum value of the 600 MPa range by formula (1), gives the result $\Theta = 0.8368$, which is in good agreement with the experimental data obtained in the proposed work.

It should also be noted that the calculations of the relative elastic modulus E/E_0 were carried out at the value of the elastic modulus for cortical tissue $E_0 = 18.7$ GPa, given in [15]. Most of the authors known to us give the values of this module in the range of 18 ÷ 20 GPa. For example, the reference book [4] gives data for the module E of the compact tissue of the femur under extension 12.3 ÷ 40.7 GPa and compression 16.5 ÷ 35.7 GPa. The significant scatter in the data is apparently explained by the conditions of preparation of test specimens, as well as by natural anatomical variability.

Graphs of dependences E/E_0 , calculated by formulas (1) and (2) are shown in Fig. 5.

Fig. 5 - Calculation of the relative modulus of elasticity E/E_0 :
a) full-range scale; b) part of graph

The lower curve in Fig. 5 corresponds to formula (1), the upper curve - formula (2). Solid symbols ▲ and ■ denote the values of the relative elastic modulus E/E_0 , calculated for the discontinuity values Θ obtained as a result of morphometric analysis (row 1 of Table 2) for formulas (1) and (2), respectively. The numerical values of E/E_0 are given in rows 2 and 3 of Table 2, respectively.

The contour symbols Δ and $\square$ denote the values Θ calculated using formulas (1) and (2) from the known values of E/E_0 given in [1, 9]. Numerical values of Θ are given in Table 2.

Note that the symbols ▲ and ■ denote the calculation of E/E_0 from the known value of Θ , while the symbols Δ and $\square$ correspond to the opposite action: the calculation of Θ from the known value of E/E_0 using formulas (1) and (2).

The discussion of the results. The graphs of the distributions of the specific density of spongy tissue and discontinuity Θ obtained as a result of morphometric research and presented in Fig. 4, show a monotonic change in the density of spongy tissue depending on the distance from the carpal articular surface, which is consistent with Wolf's law on the relationship between the structure of an organ and the function it performs in the body.

Calculation formulas (1) and (2), corresponding to different approaches to describing the properties of a discontinuous medium, represent nonlinear relationships between discontinuity Θ and the relative modulus of elasticity E/E_0 . The graphs of these dependencies, shown in Fig. 5 a, are falling curves. The value $\Theta = 0$ corresponds to solid material (cortical tissue), while $E/E_0 = 1$. When the value of the parameter $\Theta = 1$, which means no material (100% discontinuity), the ratio $E/E_0 = 0$. Note that formulas (1) and (2) are not universal for all materials in the entire range of variation of the discontinuity.

The general picture of the studied dependences and the calculation results are shown in Fig. 5 a. Since the discontinuity values determined as a result of morphometric analysis are in a rather narrow range of $0.77 \div 0.87$, for clarity, part of the graph in Fig. 5 a is highlighted in a separate Fig. 5 b. Solid symbols ▲ and ■ in Fig. 5 a, b indicate the results of calculations of the relative modulus of elasticity E/E_0 according to formulas (1) and (2) for the values of discontinuity determined by morphometric methods. The contour symbols Δ and $\square$ represent backward scaling: the calculation of Θ from the E/E_0 data of other researchers. For this, formulas (1) and (2) were resolved with respect to Θ and the root belonging to the interval $[0, 1]$ was taken as a solution to the obtained quadratic equations.

It can be seen from the tables and graphs that the discontinuity values Θ obtained in the presented work as a result of morphological analysis are preferable to use in calculating the relative elastic modulus E/E_0 according to formula (1), since this is in better agreement with other experimental data, although with this approach there are significant differences.

Conclusions.

1. Using the method of morphometry, the distribution of the density of the spongy bone tissue of the distal metaepiphysis of the radius was studied.

A decrease in the content of spongy bone tissue along the longitudinal axis of the bone has been experimentally proved.

2. Modeling the mechanical properties of spongy bone tissue, according to the known versions of models for the elastic modulus of discontinuous media, makes it possible to calculate the behavior of bone tissue in conditions of various types of interaction.

3. The comparison of the elastic moduli obtained according to our data with the results of other researchers has shown their comparability.

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О.В. Погребной

БИОМЕХАНИЧЕСКОЕ МОДЕЛИРОВАНИЕ УПРУГИХ СВОЙСТВ КОСТНОЙ ТКАНИ

Предложен метод изучения морфометрических характеристик спонгиозной костной ткани. С помощью этого метода изучено распределение плотности спонгиозной костной ткани дистального метаэпифиза лучевой кости. Уменьшение содержания спонгиозной костной ткани вдоль продольной оси кости подтверждено экспериментально. Выполнено биомеханическое моделирование механических характеристик спонгиозной костной ткани при использовании известных вариантов моделей модуля упругости для несплошных сред. Проведено сравнение полученных результатов с данными других авторов. Доказана эффективность предлагаемого метода изучения морфометрических характеристик спонгиозной костной ткани.

Ключевые слова: лучевая кость; спонгиозная костная ткань; модуль упругости; перелом; сечение.

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О.В. Погрібний

БИОМЕХАНІЧНЕ МОДЕЛЮВАННЯ ПРУЖНИХ ВЛАСТИВОСТЕЙ КІСТКОВОЇ ТКАНИНИ

Запропоновано метод вивчення морфометричних характеристик спонгіозної кісткової тканини. За допомогою цього методу вивчено розподіл щільності спонгіозної кісткової тканини дистального метаепіфізу променевої кістки. Зменшення вмісту спонгіозної кісткової тканини уздовж подовжньої осі кістки підтверджено експериментально. Виконано біомеханічне моделювання механічних характеристик спонгіозної кісткової тканини при використанні відомих варіантів моделей модуля пружності для несучільних середовищ. Проведено порівняння отриманих результатів з даними інших авторів. Доведено ефективність запропонованого методу вивчення морфометричних характеристик спонгіозної кісткової тканини.

Ключові слова: променева кістка; спонгіозна кісткова тканина; пружний модуль; перелом; переріз.

Остеопороз - це метаболічне захворювання кісток, яке характеризується зниженням кісткової маси і мікроструктурною перебудовою кісток-

вої тканини, у зв'язку з чим знижується міцність кістки і підвищується ризик переломів. Найбільш частою локалізацією остеопоротичних змін і, отже, переломів є хребці (компресійний перелом тіла хребця), шийка стегна і променева кістка (дистальний відділ, перелом Коллеса). Міцність кістки відображає інтеграцію двох головних характеристик: мінеральній щільності кістки (кісткова маса) і якості кістки (архітектоніка, обмін, мінералізація).

Проблема вивчення механічних характеристик, виявлення морфологічних особливостей структури кістки і пов'язана з біомеханічними особливостями часта руйнівність на даній ділянці мають практичний інтерес. Методи медичної морфометрії надають значні можливості для дослідження біологічних об'єктів зі складною неоднорідною структурою.

Метою роботи є вивчення розподілу щільності в області дистального метаепіфізу променевої кістки, на ділянці, найчастіше схильній до переломів при розвитку остеопоротичних змін. На підставі отриманих експериментальних даних провести біомеханічне моделювання пружних констант кісткової тканини.

За результатами морфометричного аналізу побудовано графік розподілу питомої щільності спонгіозної тканини в залежності від відстані від зап'ястної суглобової поверхні.

За допомогою запропонованого методу вивчено розподіл щільності спонгіозної кісткової тканини дистального метаепіфізу променевої кістки. Зменшення змісту спонгіозної кісткової тканини уздовж поздовжньої осі кістки підтверджено експериментально. Виконано біомеханічне моделювання механічних характеристик спонгіозної кісткової тканини при використанні відомих варіантів моделей модуля пружності для несучильних середовищ. Проведено порівняння отриманих результатів з даними інших авторів. Доведено ефективність запропонованого методу вивчення морфометричних характеристик спонгіозної кісткової тканини.

*Oles Honchar
Dnipro National University
Dnipro, Ukraine*

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