densitometry test, bone tissue,
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SIMULATION OF THE REACTION OF X-RAY RADIATION WITH AN OBJECT WHILE DENSITOMETRY TESTS

The computer modelling of absorption effect of X-ray radiation in the bone tissue was analysed. An image, which is produced as a result of X-ray absorption was computed based on the absorption law. The simulation enables to define dimensions and resolution of space where the experiment will be realised. A model of a sample contains information about its geometry and distribution of density. It can be made as simple solids or loaded from external source, like files. This method may be useful to load information about bone microstructure into the simulation space. A source of X-ray radiation was defined as a plate, which has initial radiation intensity. Rules of radiation propagation were simplified to straight model where radiation propagates in the direction perpendicular to the surface of detector which records an image. The image is generated by computation of partial absorption for each space elements. The results of simulation of model of micro-structure of bone tissue are presented. They can be useful to show when densitometry test does not contain accurate and full information about bone tissue. It may by helpful in the future while searching for reasons of incomplete correlation between mineral density and mechanical strength.

1. INTRODUCTION

A densitometry test forms the basis for the diagnosis of susceptibility to fractures. Such a test can be conducted using a number of techniques; however the World Health Organization (WHO) and International Osteoporosis Foundation guidelines currently recommend Dual Energy X-ray Absorptiometry (DEXA), as an acceptable technique for conducting densitometry test of proximal femur [13].

A digital X-ray detector eliminates the necessity of using a photographic plate. After diagnosis, the test results are stored in a computer file. It is possible to select regions for analysis from the image using a semi-automatic procedure. Afterwards, the software makes a densitometry diagnosis using an averaging algorithm. The obtained result contains information about the sum of superficial bone mineral density both cortical and trabecular. The result is presented in the unit of mass per unit of surface (g/cm^2). T-score and Z-score, which are also reported, are more useful in clinical application.

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Some researchers claim that there is a relation between the bone's mineral density and the risk of fracture [9],[15] ,[1], however, it is worth noting that from the mechanical point of view, decreasing values in the parameters of bone tissue stiffness determine the risk of fracture. These parameters are not always directly connected to the bone's density, as confirmed by known clinical cases. According to Dutch research, the absolute number of fractures is not dependent on BMD. In 63% of cases, fractures occurred despite correct BMD value, or in osteophenia [8]. The result of Dutch research was also confirmed in a Polish study [14]. Additionally, the correlation of bone mineral density with mechanical parameters has also been researched [10].

In the DEXA method, the characteristic unit is bone mineral density measured as g/cm^2. In view of the two-dimensional character of the data medium – bone photography – measuring mass quantity per volume unit is impossible. Moreover, only the sum of cortical and trabecular bone measurements is presented. Quantitative Computer Tomography (QTC) provides better results including mass unit per volume unit (g/cm^3) and separate estimates for cortical and trabecular bones' measurements. In this respect, QTC is the most precise measurement method [15].

The scale of the image in both methods has resolution which does not take into consideration the structure's shape. Only the information about the quantity of mass per surface (or volume) unit is given. The information about structure remains inaccessible.
Only BMD of healthy bone will be equal to its real density. For a bone with similar quantity of material, but a weakened structure, BMD is only seemingly correct. Present density of the structure, which actively participates in the transmission of loading, will be smaller.

In the previous laboratory study there was confirmed that a connection between bone mineral density and the parameters of mechanical stiffness would be definitely different [5],[6]. The mechanical micro-properties of bone tissue samples were measured and compared with the results of the densitometry test. The samples have been modified in order to change their biomechanical properties. The correlation between bone mineral density and mechanical parameters such as Young's modulus was very low.

To find the reasons of this low correlation and explanation why it is present, there is a need to deliver qualitative and quantitative results of study. The previous study [6] was only initially laboratory research, which based on not so many samples from animal bone. Precise analysis of the state in human bone tissue should contain many data from human speciments which should be statistically significant. Computer simulation was realized before preparing a schedule of wide research on the human speciments. The aim of simulation was to calculate a reaction between X-ray radiation and model of bone tissue. The calculation of behaviour of X-ray radiation as a propagation process through the bone was modelled; as a similar to the densitometry test.

The simulation was prepared to obtain quantify information about conditions of densitometry measurement. The main expectation from computer calculations was to record when densitometry test can deliver incorrect results.

2. MATERIAL AND METHODS.

The simulation of interaction between X-ray radiation and tested object was realised to calculate parameters which usually are obtained from standard densitometry test. Fundamental functions of densitometry equipment were included in the modelling of simulation's conditions. Figure (1) presents main parts of the densitometry equipment: source of X-ray, space where patient's bone (tested object) is placed, and detector of X-ray.

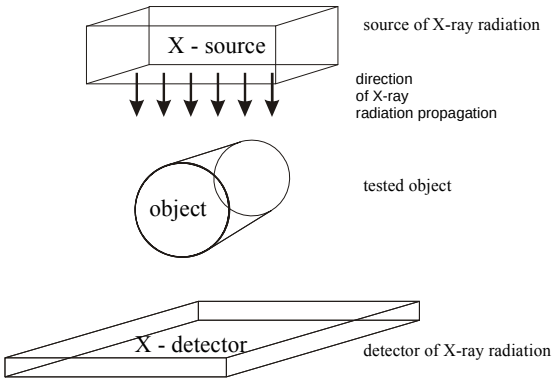

Fig. 1. The schema of densitometry equipment

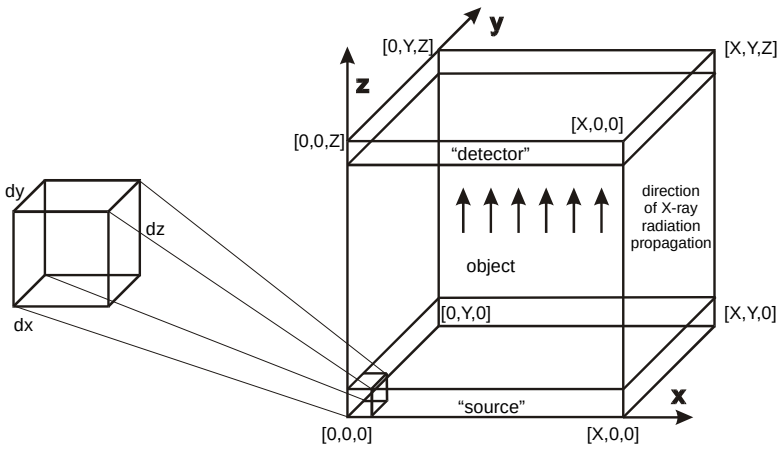

Fig. 2. The schema of space of simulation and separate element of space

The discrete space of simulation was defined in the rectangular three-dimensional coordinate system (x,y,z). The system has a cubic shape and dimensions defined as [0..X,0..Y,0..Z].

Along every coordinate axis minimal units was created as a (dx,dy,dz). It is also resolution of computation. Figure (2) presents schema of space of simulation which was created to realise computation. As it is visible in the figure, there are the regions which perform functions of source and detector of X-ray. The "source" was defined as a plate which has dimensions equal [X,Y,dz] and which is placed on the lower part of the

simulation space. (co-ordinates of the plate position are equal [X,Y,0]). Whereas the plate which has the same dimensions equal [X,Y,dz] and it is placed on the upper part of the simulation space. (co-ordinates of the plate position are equal [X,Y,Z]). This plate performs the function of detector of X-ray. Between „source" and „detector" there is a space where model of tested object is placed. The dimensions of this space do not exceed dimensions of simulation space therefore they are contained maximal in the cubic with dimensions equal [dx..(X-dx),dy..(Y-dy),dz..(Z-dz)]. In the aim of the simulation several indispensable assumptions were made to make easier calculation of complex physical processes, which proceed as a reaction between X-ray radiations with an object in densitometry test.

In the presented simulation following characteristic of simulation's space was assumed:

"Source"

„Source" is defined by unitary plate where for each element value of radiation intensity I_o was specified. It was assumed that intensity is constant for each element and does not change while emission. A surface of the "source" is parallel to the surface of "detector".

„Detector"

„Detector" (recording matrix) is defined by unitary plate where for each element the same value of sensitivity was specified. A function of detection is realised based on a rule of proportional response for the input by X-ray radiation.

„Object"

A modelling of object consists on defining his dimensions and characteristic of material which was used to made an object. In the presented simulation, characteristic of material means to define a value of absorption factor of X-ray radiation. For each element of space can be defined other value of factor.

3. PRINCIPLES OF COMPUTATION OF REACTION OF X-RAY RADIATION WITH THE MATTER.

Process of reaction of X-ray radiation, with the matter procedure in accordance with absorption law - described by equation (1) [17].

$$I = I_0 \exp(\mu l) \qquad (1)$$

where:
I – radiation intensity after transition through the tested object which has thickness equals l
I_0 – incident radiation intensity
μ – linear factor of absorption
l – thickness of an object

A straight model of propagation of radiation was assumed, where radiation is emitted from the "source" with intensity equals I(x,y,0). The radiation propagates in the perpendicular direction to the flat surface of "detector". After transition through the object radiation which is emitted from element of "source" (coordinates equal [x,y,0]) inside on the element of "detector" (coordinates equal [x,y,Z]). In the presented simulation there is omission in computation of absorption effect from not perpendicular directions.

The rule of computation of absorption in the discrete space of simulation was defined by equation (2). For each elementary voxel the absorption was computed. It is realised with accordance of thickness (dz_i) and factor of absorption (μ_i) which are presented in current voxel *i*.

$$I_{xy} = \sum_{i=1}^{Z} I_{(i-1)} \exp(\mu_i dz_i) \qquad (2)$$

where:
I_{xy} – radiation intensity after transition through the simulation space, which is recorded by the element of „detector", which has coordinates equal (x,y).
$I_{(i-1)}$ –radiation intensity inputted on the element for which absorption is computed
μ_i – linear factor of absorption for current element
dz_i – thickness of current element in direction of radiation propagation

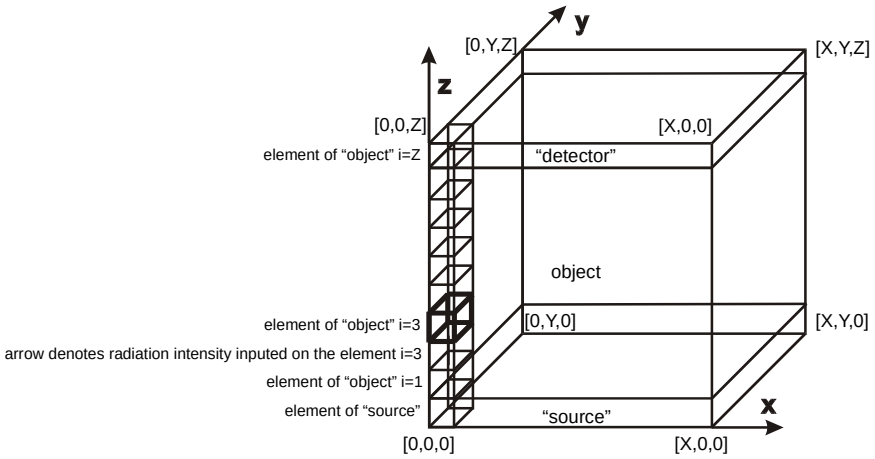

Fig. 3. The schema of iterative computation of absorption in the simulation

The computations start in the element which is placed in the neighbourhood of "source". In this localisation intensity inputs on the object is equal to intensity from "source". Absorption in the following discrete elements of space computes in accordance of iterative algorithm, which allows preceding movement along the direction of vertical axis z. Schema of iteration, is presented in figure (3). Calculated value of intensity after transition through the first element is input value to the compute absorption in the next element. Value of input determines incident intensity for this element. The process is being realised until reaching an element which is a neighbour of "detector". Value of intensity radiation after propagation through all elements of simulation space is recorded in "detector". If in the

space there was an object (or its fragment), there was non-zero value of absorption factor. It caused a decrease of radiation intensity. For each element of „detector", computation of radiation is realised with procedure of summation of partial absorptions. They are proceeded in each space element, which is on the radiation way. The summation is realised along all elements which are present on the shortest distance between "detector" and "source"

4. MODEL OF BONE TISSUE.

It is assumed that the model is constructed on the base of trabecular bone tissue, which is characterized not only by density but also by microstructure construction. The model contains spatial distribution of density and a construction of microstructure.

In presented simulation, the model of tissue was simplified in the aim to reduce analysis of a problem only to two directions of radiation propagation. Model consists of plates localised in some distance from each other. Density of material was defined for the places. The factor of absorption for this material was different than for the rest of model space. Schema of the model is presented in figure (4) and its characteristic is described in table (1).

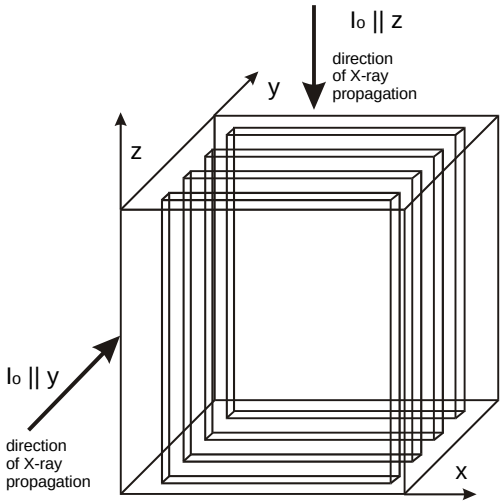

Fig. 4. The schema of the model which was used in the simulation

Table 1. Characteristic of the model which was used in the simulation.

dimensions	
width (x)	10 mm
length (y)	10 mm
height (z)	10 mm
factor of absorption	
for plates μ_p	0,2
for space μ_s	0,001
distance between plates	0,1 mm
thickness of plates	0,1 mm

The ability to identify changes in absorption of radiation in the model can be an example how microstructure is identify in the densitometry test.

5. RESULTS

The result of simulation is presented as a densitometry image and numerical parameters. In the image, shades of grey are presented; they are the result of commutated radiation intensity which is recorded in the "detector" after transition through the object. Numerical parameters enable quantitative estimation of differences in the image.

The results of simulation are presented on two figures. Figure (5) shows the result for the direction of radiation propagation parallel to the direction of placed plates in the model. Figure (6) presents result for the directions of radiation propagation perpendicular to direction of placed plate.

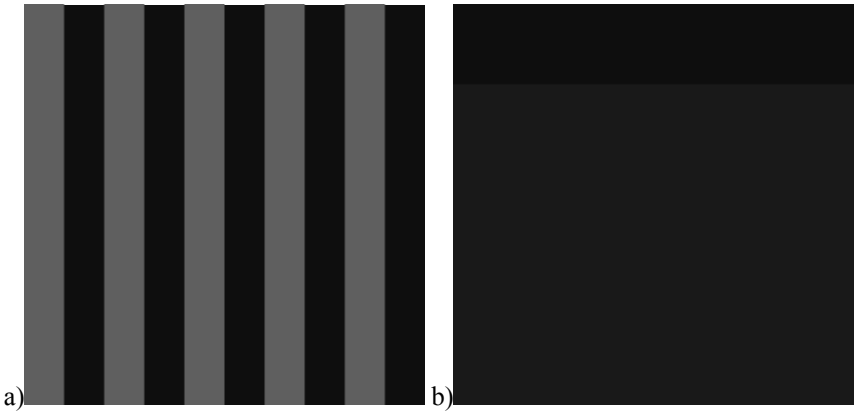

Fig. 5. Image which shows distribution of radiation intensity for the parralely propagation direction to the plates: a) resolution equals 0,1mm; b) resolution equals 0,2mm

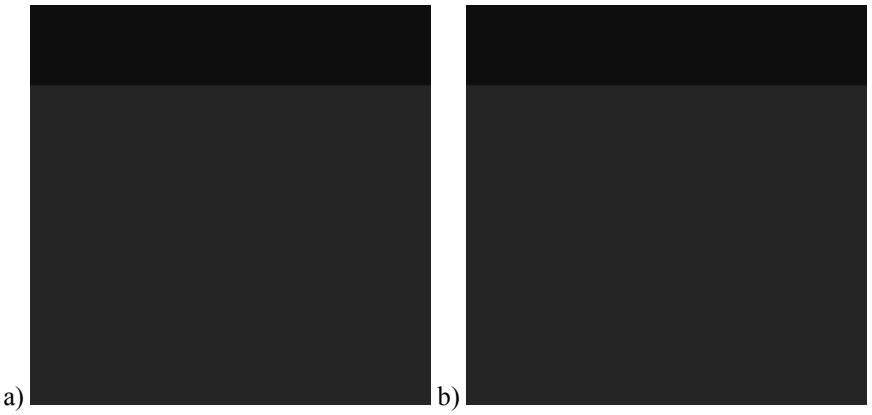

Fig. 6. Image which shows distribution of radiation intensity for the perpendicular propagation direction to the plates: a) resolution equals 0,1mm; b) resolution equals 0,2mm

6. DISCUSSION

Distances between plates are examples of changes in the structure which are presented perpendicular to the direction of radiation propagation. This situation is presented for each porous compartment in the trabecular bone which axis of symmetry is parallel to direction of radiation propagation. It can be observed that for adequate large distance between plates recording in "detector" is possible. However when the distance between plates decreases under "detector" resolution, precise identification of those changes is impossible.

The result of simulation of radiation propagation perpendicular to the direction of placed plates can be useful to estimate identification quality of porous compartment, which axis of symmetry is localised perpendicular to propagation direction. As it can be observed, regardless of distance dimension between the plates and "detector" resolution, those changes are not able to be identified in the image. They have influence only for a final and reckoned value of radiation intensity.

7. CONCLUSIONS

The identification of porous compartments which have axis of symmetry parallel to the direction of radiation propagation can be incorrect. A precision of identification can be corrected in the simulation by increasing the resolution of 'detector". However in the densitometry equipment, it can be realised by using recording elements which have smaller dimensions. It should provide the increase of resolution of recording X-ray radiation quantums. The identification of porous compartments which have axis of symmetry perpendicular to the direction of radiation propagation is impossible. A precision of identification can be corrected in the simulation by developing simulation and realisation of additional computation for different angle of radiation propagation. However in the densitometry equipment realisation of the second test is impossible. Because of this aspect, result of densitometry test will not be complete. It will contain information about density but the information about microstructure will remain inaccessible.

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