micro-tomography, X-ray propagation, bone microstructure
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MODELING OF X-RAY PROPAGATION IN BONE MICROSTRUCTURE

This paper presents some results concerning the analysis of X-ray propagation through biological structures. We introduce a physical model of the phenomenon and a numerical method based on this model for simulation of X-ray radiation propagation. The proposed method enables generation of radiological projections like those in the computed tomography or microtomography. We have focused our attention on the attenuation of X-ray radiation in bone tissue. Our computational model enables simulation of radiation propagation in the virtual specimen. The virtual bone microstructures used in our experiments are derived from the microtomography datasets of real bone specimens. The main advantage of our approach is that we can change the microstructure of the virtual sample in many ways by using the image processing methods. Results presented in this paper contain simulations of X-ray propagation for modified and unmodified trabecular microstructures as well as the visualization of the radiation intensity distribution for the simulated cases. With this new simulation technique, it is possible for example to analyze the propagation of X-ray radiation for different pathologic types of bone microstructure (e.g. virtually generated osteoporosis).

1. INTRODUCTION

In the nearly 110 years since the Roentgen's discovery of X-rays, the study of radiation propagation has become a mature field of science and its exploitation for medical imaging and diagnostics forever changed the course of medical history. X-ray propagation through the matter is one of the most important physical phenomena which have been used in many diagnostic and therapeutic devices and techniques. Some of them like for example computed tomography or micro-tomography are nowadays commonly used in clinical diagnostics and research. They allow to study *in vivo* and *in vitro* the bone properties, like bone microstructure or bone mineral density [1]. The simulation of the X-ray propagation in bone tissue using numerical methods was our main motivation to carry out this research. Analysis of X-ray propagation is quite complex and generally needs a probabilistic approach and computation of stochastic events at the atomic level. The most important interaction mechanisms of X-ray radiation with matter are explained in the next chapter. There will be explained the physical and numerical model for simulation of X-ray attenuation process at the bone microstructural level. Figure 1 shows the measurement process of the transmission tomography for single projection. The estimation of the X-ray attenuation for a given propagation direction and the computation of the resulting radiation intensity on the X-ray detector

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is the crucial basic step in the simulation of the computed tomography technique. The idea of making projections is similar for both computed tomography and micro tomography devices and they differ only in the technical design. In the next chapters we describe the main components of our simulation approach: the applied physical model describing the X-ray propagation and interaction with bone microstructures, and the numerical model to estimate the radiation intensity at the detector after attenuation in the virtual bone specimen. After that we present the simulation results for different bone microstructures that have been virtually modified by image processing methods. At the end we will discuss the results and formulate some conclusions.

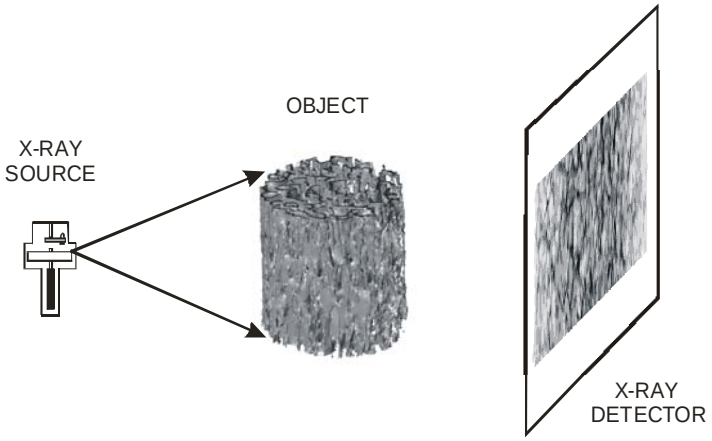

Fig. 1. The measurement process of the transmission tomography for single projection.

2. MATERIALS AND METHODS

Based on the physical definition of X-ray radiation X-rays can interact with matter in several different types of interactions [2]. Attenuation of X-rays in biological materials takes place by several different mechanisms, some of them are due to absorption, and others due to scattering of the beam. It can result in decreasing of its energy as well as in changing of radiation direction. In such cases an X-ray will exist after the initial interaction in the form of a scattered X-ray, characteristic X-rays, or annihilation radiation photons. The types of interactions are the photoelectric effect, Rayleigh scattering, Compton scattering, pair production, and triplet production [2]. Considering the fact that in medical diagnosis like computed tomography or micro-tomography the applied X-ray energy lies between 20 keV and 150 keV. In this range of energies there are the three most important interactions which have influence on the attenuation of X-rays: photoelectric effect, Compton scattering and coherent scattering. In our area of interest the Compton scattering effect is the most important one. The influence of other interactions in biological materials makes up less than 3% of the whole attenuation [4]. It is also due to chemical content of the human body. Over 99% of all chemical elements occurring in human cells like H^{1}, C^{6}, N^{7}, O^{8}, Na^{11}, Mg^{12}, P^{15}, S^{16}, Cl^{17}, K^{19}, Ca^{20} are light, and there is only vestigial amount of elements with atomic number higher then 20 [4]. The Compton scattering involves the inelastic scattering of an X-ray photon by an atomic electron. In effect, an incident X-ray photon of energy is scattered by the medium, and the products of the interaction include a scattered X-ray photon, an electron, and an ionized atom [2]. The attenuation of X-ray in a biological specimen can be calculated according to the Lambert-Beers law [2,4]. It is the governing equation in the numerical implementation of the X-ray attenuation model used in our simulations.

2.1. COMPUTATION OF INTERACTIONS OF X-RAY RADIATION WITH THE MATTER

The computational model of X-ray attenuation in the discrete specimen space has been proposed in our earlier work on simulation of the densitometry measurement [3]. In this work, we apply the model of X-ray attenuation to compute a single tomography projection. To define the geometry of the bone microstructure, data acquired by micro CT scanner has been used. The sample was dissected from the long bone of a calf. It was a 9.22 millimeters height cylinder with diameter equal to 8 millimeters. The sample of a dry trabecular bone tissue has been scanned in Department of Biomaterials in School of Dentistry at University of Athens in Greece. To avoid the computational bottlenecks the original dataset of resolution 1024×1024×978 has been scaled down to the resolution of 256×256×256 voxels. The reformatted transversal cross-sections have been used to define the spatial distribution of bone density for our bone model in the simulation space. The simulations have been performed using the bone sample presented in Figure 3a. The attenuation of X-ray radiation has been computed according to the principles of computed tomography [2,4]. The direction of X-ray propagation was perpendicular to the main axis of the sample. The model of the parallel X-ray propagation has been chosen to calculate the projections. Radiation intensity has been computed for each voxel of the simulation space according the proposed methodology (see Figure 2). The proposed approach gives us the possibility to analyze quantitatively the attenuation process of X-ray radiation in the bone microstructure.

The geometry of the simulation space and the rules for the numerical estimation of radiation attenuation are presented in Figure 2. Attenuation of X-rays is calculated using the iteration procedure defined by Equation 1 [6]. For each elementary voxel *i* along the X-ray path the radiation intensities I_i have to be computed. It is realized taking into account the voxel thickness (Δx_i) and factor of attenuation (μ) which are defined for each voxel of the simulation space:

$$I_i = I_{i-1} e^{-\mu_i \Delta x_i} \tag{1}$$

where I_i is the radiation intensity after transition through the *i*-th voxel of the simulation space. I_{i-1} is the radiation intensity estimated for the previous *i*-1-th voxel along the actual radiation path from the X-ray source. μ_i is the attenuation coefficient depending on the density of microstructure. Δx_i is the thickness of the *i*-th object voxel (see Figure 2). The estimation of radiation intensity which is recorded by each discrete element of „detector" takes into account all voxel intensities along the ray path starting at the X-ray source plane. I_0 is the predefined radiation intensity of the X-ray source in the model. I_n is the resulting intensity estimated for each discrete element of the detector plane according to the governing equation (see Eq. 1).

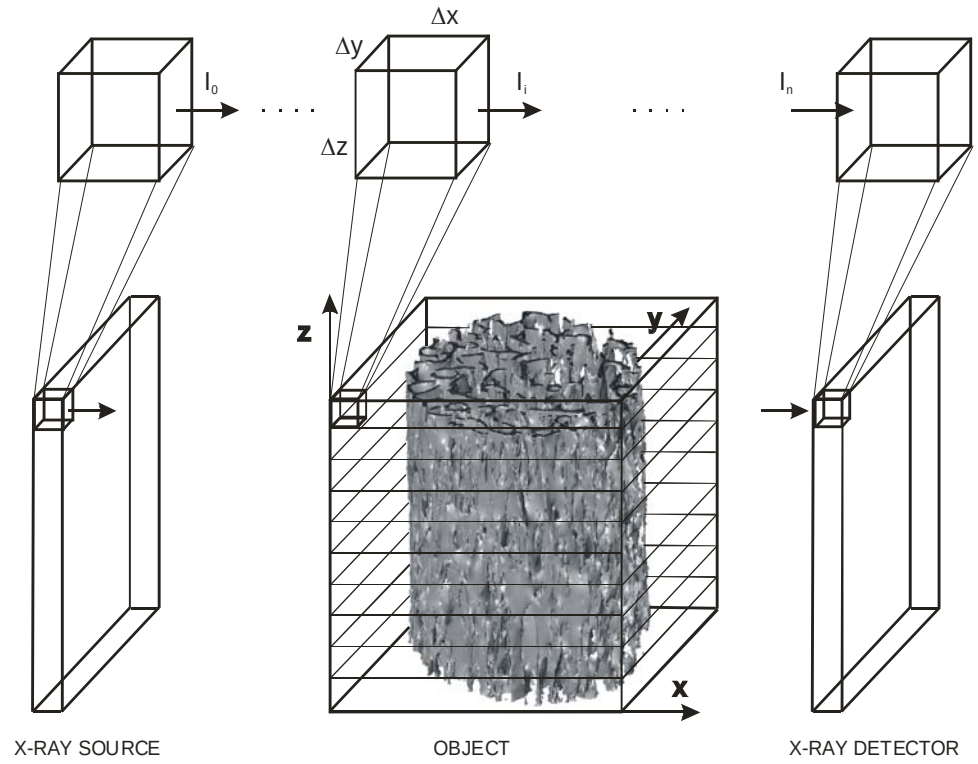

Fig. 2. The geometry of the simulation space and the rules for the numerical estimation of X-ray attenuation

3. SIMULATIONS AND RESULTS

The simulation of the X-ray propagation through the bone microstructure based on the above described computational model has been performed for the virtual specimen model. One of the main goals of this research was to analyze how the change of bone microstructure influences the distribution of radiation intensity in the generated projections. Another intention of this work was to investigate the spatial attenuation of X-rays interacting with the bone microstructure. A modification of the specimen trabecular surface has been proposed as the first approach to change the bone microstructure. The modification of the virtual specimen model has been done by applying the mathematical morphology operations from the image processing domain [7]. The three-dimensional erosion of the virtual bone microstructure has been performed to induce similar (but not the same) effects as in case of osteoporosis. The standard cubic erosion kernel 3 voxels wide with 6-connectivity has been used and after this procedure the trabecular surface parameter has been estimated. Table 1 shows the results of those estimations for both samples. Trabecular surface after erosion has been reduced by 2891 voxels (27%) and the new trabecular surface was equal to 7831 voxels (73% of the original sample). Intra-trabecular surface was growing up from the previous value of 251421 voxels (100%) to 254313 voxels (101%) after erosion. There has been changed the proportion between the number of trabecular and intra-trabecular surface voxels. Simulations of X-ray propagation have been performed for the virtual original specimen and for the specimen after erosion. The computation of X-ray attenuation for the entire sample let us obtain the distribution of the radiation intensity in detector. The simulation has been carried out for the initial radiation intensity equal to 80 keV. The computation has been performed through all voxels of the modeled object in direction of X-ray propagation starting at the X-ray source, propagating through the virtual microstructure and ending in the detector. Values of radiation intensities have been saved after

every step of the iteration process according to Eq. 1, what means that we obtain information about radiation intensity for each point (voxel) of the simulation space.

Table 1. The trabecular surface parameters for the original sample and for the eroded one.

		Original sample	After erosion	Δ
Intra-trabecular surface	#voxels	251421 (100%)	254313 (101%)	-2891 (1%)
Trabecular surface	#voxels	10723 (100%)	7831 (73%)	2891 (27%)

The differences in the distribution of the radiation intensity for the original virtual specimen and for the specimen modified by erosion can be observed and analyzed in the numerical data. But for better understanding and interpretation of our simulation outcomes the generated numerical results have been worked out as 3D images (see Figure 3b). The numerical data has been converted into color-coded datasets and rendered by using volume rendering method. The transfer function assigns to each voxel some opacity value and intensity-depending color (according to the present below color scale). The rendering results can be analyzed in Figures 3 and 4. For better perception of simulation results the visualization has been generated for smaller subspace of the entire modeling sample. The visualized sample has dimension of 50×50×80 voxels and the size is 1.91×1.91×3.56 mm.

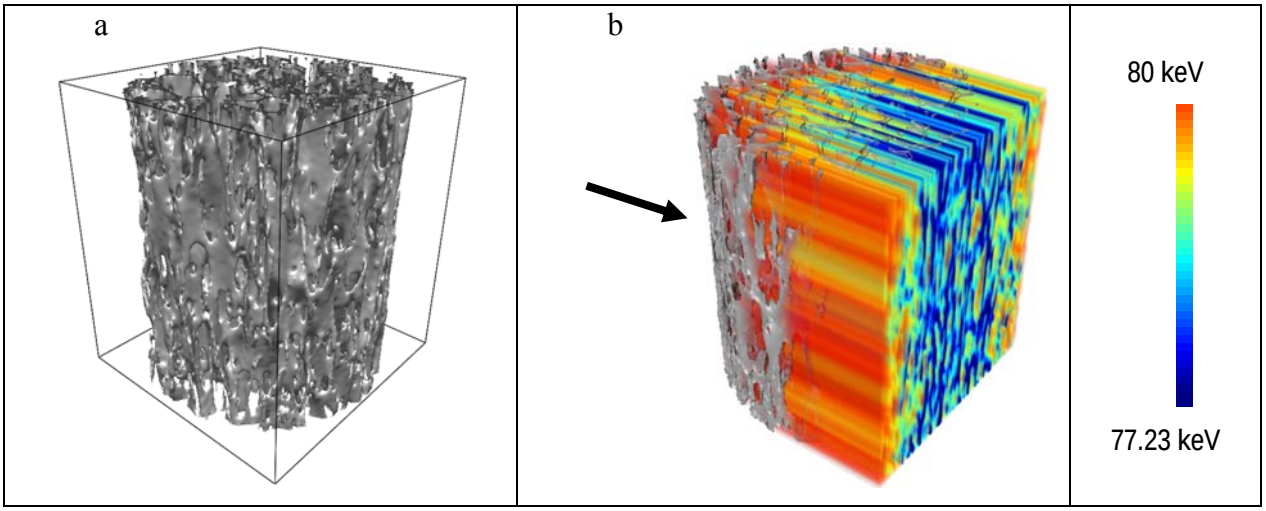

Fig. 3. Three-dimensional images of the virtual specimen, a) surface rendering of the bone microstructure model; b) superposition of the bone geometry and the visualization of X-ray radiation computed during propagation through the virtual specimen.

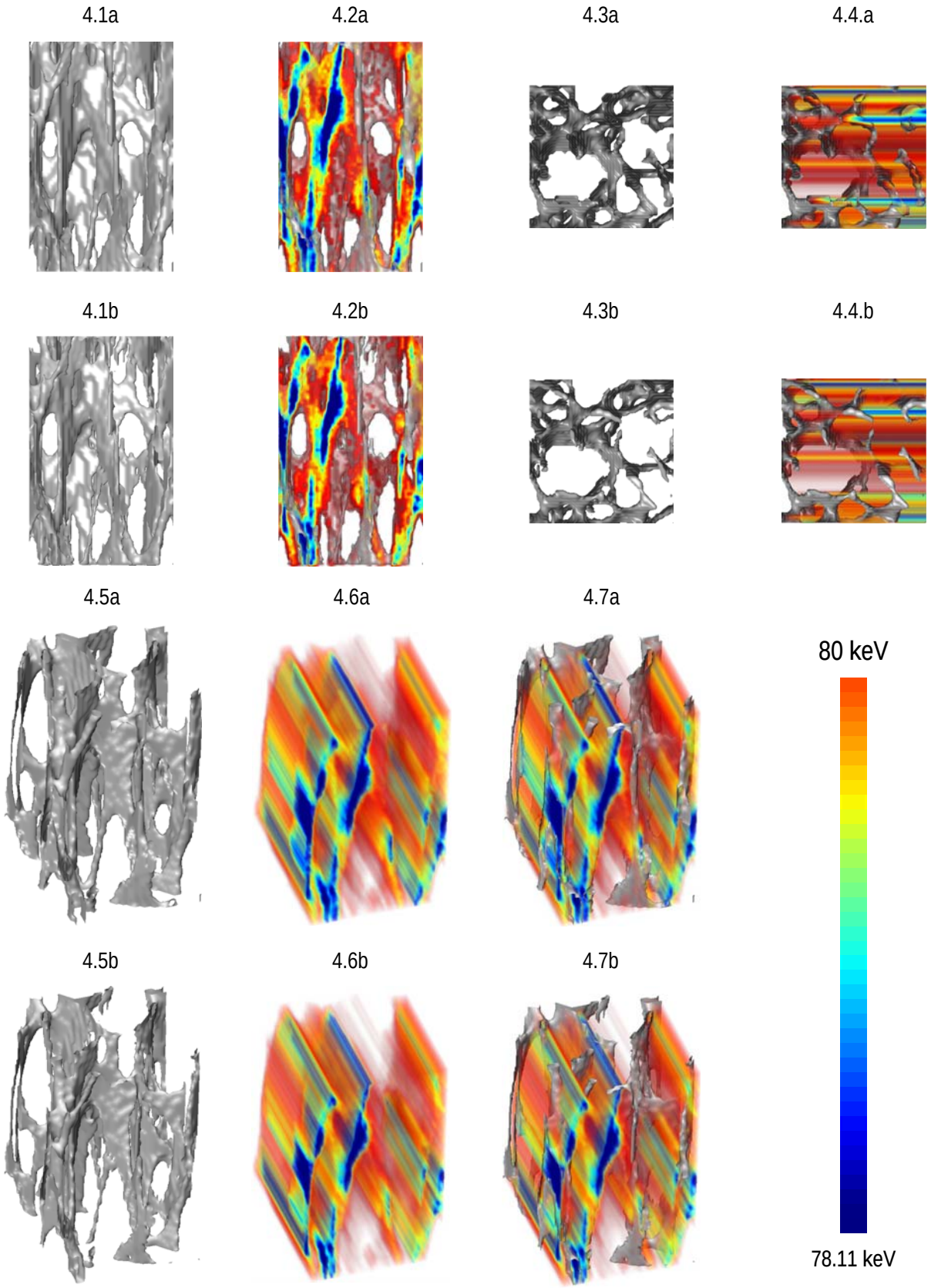

Fig. 4. The sample geometry and the distribution of X-ray radiation intensity during the propagation through the sample.

Images of the original geometry are presented in Figure 4.1a and 4.3a and in Figure 4.1b and 4.3b for the sample after erosion. We can see that holes in the sample after erosion are larger and trabecules are thinner. The distribution of radiation intensity in the original sample is shown for detector view in Figure 4.2a and for the top view in the Figure 4.4a. The images 4.2b and 4.4b show results for the sample after erosion. The images 4.2a and 4.2b as well as 4.4a and 4.4b show radiation intensity superposed on the geometry. The next images show the perspective views. In Figure 4.5a geometry of the original sample is presented, and the geometry of the sample after erosion is shown in Figure 4.5b. In Figure 4.6a and 4.6b the distribution of radiation intensity for both samples is shown before and after erosion accordingly (without sample geometry). The Figures 4.7a and 4.7b show superposition of the estimated radiation intensity with the sample geometry. It is easy to observe the differences in the X-ray radiation intensity distribution caused by the modified sample geometry.

4. DISCUSSION AND CONCLUSIONS

The proposed model of the radiation attenuation allows modeling of X-ray propagation in biological medium. 3D modeling has been applied to simulate the propagation of X-rays in the virtual bone microstructure. The trabecular structure of the virtual specimen has been modified and the simulation of the X-ray propagation through both samples has been carried out. As it could be expected, there exist differences between X-ray intensity for original sample and sample after erosion. After applying of erosion procedure the total trabecular surface of the specimen has been reduced to approximately 73% of the original one. It is substantial reduction of the trabecular surface in compare to the real osteoporosis effects. The influence of this microstructure modification on the distribution of X-ray intensity in the detector plane can be quantified by using our approach. The intensity of X-rays which has been calculated in the simulation process can be used to construct a tomography projection. The computed projections of the virtual bone microstructure (before erosion) are in a good agreement with the original specimen projections obtained from the micro CT scanner. Assessment of the radiation intensity for each point of X-ray trajectory can be provided only by the proposed simulation approach. Measuring of the X-ray attenuation during propagation through the microstructure is technically impossible. With this new simulation technique, it is possible to make significant progress in the area of medical imaging and bone diagnostics. The method allows inducing in virtual specimen different pathological processes, like for example during osteoporosis. Our goal in this work was to simulate changes in the bone microstructure according to trabecular surface as well as the trabecular thickness. The modification of other bone microstructure parameters let us assess the changes of radiation intensity for different trabecular bone patterns. In this way we are able to study and analyze quantitatively how the distribution of radiation intensity in the X-ray detector depends on changes in the bone microstructure and its characteristics.

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