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SIMULATION OF LASER RADIATION PROPAGATION IN INHOMOGENEOUS MEDIA WITH COMPLEX GEOMETRY

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МОДЕЛИРОВАНИЕ РАСПРОСТРАНЕНИЯ ЛАЗЕРНОГО ИЗЛУЧЕНИЯ В НЕОДНОРОДНЫХ СРЕДАХ СО СЛОЖНОЙ ГЕОМЕТРИЕЙ

A mathematical model has been developed. It makes possible to analyze the process of the three-dimensional propagation of laser radiation in inhomogeneous media with a complex geometry using the proposed modification of the Monte Carlo method. The model also allows to carry out the calculation of the distribution of the absorbed laser energy density in multilayered materials with complex geometry and can be used in solving problems of analysis of thermal fields visualization. Those problems arise in irradiated tissues.

LASER RADIATION, MULTIBIOLOGICAL TISSUE, MONTE CARLO METHOD, INGOMOGENEITY, MULTIPLE SCATTERING.

Построена математическая модель, позволяющая с помощью предложенной модификации метода Монте-Карло анализировать процесс трехмерного распространения лазерного излучения в неоднородных средах со сложной геометрией. Модель позволяет проводить расчет распределения плотности поглощенной энергии лазерного излучения в многослойных материалах сложной геометрии и может использоваться при решении задач анализа визуализации тепловых полей, возникающих в облучаемых тканях.

ЛАЗЕРНОЕ ИЗЛУЧЕНИЕ, МНОГОСЛОЙНАЯ БИОЛОГИЧЕСКАЯ СРЕДА, МЕТОД МОНТЕ-КАРЛО, НЕОДНОРОДНОСТЬ, МНОГОКРАТНОЕ РАССЕЯНИЕ.

I. Introduction

Optical methods of diagnostics of the biological tissues are now becoming more and more widespread. The main advantage of these methods is their non-invasiveness. Using low-intensity laser radiation in the visible and near-IR region as a sounding signal does not have significant damaging effects on the studied biological media. In this context the questions of using mathematical models that would adequately describe the propagation of light in biological tissues, acquire additional relevance. Such models should describe not only the propagation of radiation in terms of the multiple scattering, but they also are supposed to solve the problem of determining the flow of radiation emerging from the medium of the illuminated surface. This is due to the fact that most modern diagnostic methods are based on the detection of reflected and backscattered light.

The theory of radiative transfer is one of the most common theoretical description of light propagation in turbid media. However, the analytical solution of the problem of light propagation in multi-component biological tissues is quite complex, even in simple cases. If we consider heterogeneous tissue or the tissue of complex geometry, then obtaining an analytical solution is almost impossible. In such cases the required solutions can only be obtained by numerical methods. However, most of the known methods do not allow full determining the changes in the optical and geometrical parameters of the medium due to the presence in it various irregularities. From the point of view of modeling, «visualization» of such objects is to use the most appropriate statistical Monte Carlo (MC) method. It is based on the concept of the radiation propagation in the medium in the form of a flow of model wave packets, each of which being formed by a set of photons of a certain «class» with a given energy and propagation direction. This means that the model package exhibits definite properties such as phase and polarization and is a kind of quasiparticle energy carrier, and is capable of forming an interaction with the medium of similar, but less energetic particles.

The mathematical model of the process of three-dimensional optical radiation propagation in living tissue is described in this paper. It is assumed that the model medium volume is a set of addressable (indexed) volume elements of three-dimensional space. Selecting a possible model for the event package is calculated by its interaction with either the elementary volume or the surface, if the latter is the boundary between the layers with different optical characteristics.

II. Simulation Methods of Laser Radiation Propagation in Complex Tissues

With regard to the problem of light propagation, photons motion in a medium is simulated. In other words, «random path» of photons is simulated on the basis of the laws that determine the radiation distribution in the tissue. The movement trajectory is expressed by the probability density function $p(x)$, which depends on the medium macroscopic optical parameters [1 – 5]. These parameters include the absorption coefficient, the scattering coefficient and the anisotropy parameter. Fresnel law is used to account for the reflection or refraction at the interface of two subdomains. Fig. 1, *a* shows an example of the photon trajectory in the medium. Model is based on the radiative transfer equation.

It is believed that the particles, which are scattered and absorbed, are spherically symmetrical, and therefore the average indicatrix of scattering can be used in our calculations. Using this model and comparison of numerical calculations and experimental results have shown that this approximation satisfactorily describes properties of most biological tissues.

III. The Simulated Experiment Scheme

The action of UV and IR laser radiation on the human epidermis is widely used in medicine. The biological medium is inhomogeneous, and its optical parameters are complex functions of spatial coordinates. However, the medium can be divided into fairly small subregions, within which the optical properties of the medium can be approximately specified. The simplest approximations are those of constant, linear, and quadratic functions. For modeling by Monte Carlo method in three-dimensional space, a very important factor is how to carry out such a division.

a) *b*)

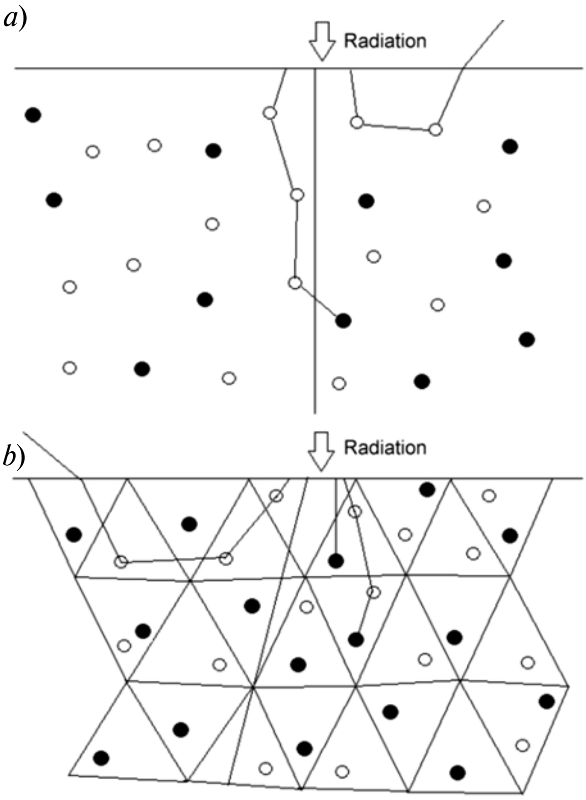

Fig. 1. An example of the photon trajectory in the medium
(The open and shaded circles – respectively absorbing and scattering centers)

The finite-element method provides a convenient set of tools for describing complex media. The geometry of the medium is described in this paper as a finite-element network (Fig. 1, *b*). The use of Monte Carlo method to model radiation propagation with such a specification of the medium has a number of features that are considered in this paper. The simpler the shape of the partitioning elements, the fewer computational resources are required for the calculations. Therefore, the use of tetrahedra as network elements makes it fairly easy to make a transition between elements to go beyond the limits of an element and to find a packet inside a network element. Certain criteria need to be developed to determine the quality of the network. The network by means of which the calculated region is approximated by partitioning into elementary cells is one of the main factors that determine the accuracy and convergence of the numerical solution of the problem.

According to the theory [6], the properties of the network mainly depend on the shape of the partitioning elements. Networks are regarded as high-quality in such an estimate when each element is a regular or close-to-regular tetrahedron. Consequently, a network will be considered low-quality if it contains degenerate or close-to-degenerate elements. With such an approach, the starting geometry of the calculated region can be arbitrary. The case in which the medium contains an internal closed inhomogeneity can be of practical interest. Problems of the propagation of radiation with wavelengths of 400 and 800 nm were therefore chosen as test problems to estimate the accuracy and adequacy of the developed algorithm. Skin has an inhomogeneous structure and accordingly inhomogeneous optical parameters. A medium consisting of several layers: the stratum corneum, the epidermis, and the dermis with a closed inhomogeneity of complex shape – was chosen as the calculation medium. The closed inhomogeneity is modeled in the form of a complex figure bounded by two ellipsoidal surfaces; an additional layer which models air is also introduced.

Fig. 2 shows the geometry of the calculation medium subjected to laser irradiation. The center of the beam is displaced relative to the coordinate origin along the x axis by 0.001 cm and is directed perpendicularly upwards, and its radius is 0.001 cm. The absorption coefficient is fairly high for radiation with wavelength of 400 nm; therefore, it must be strongly absorbed, without penetrating deep inside the medium.

When a photon is deflected by angle θ, it is assumed that it is deflected axially symmetrically relative to the initial propagation direction at azimuthal angle ψ, which is

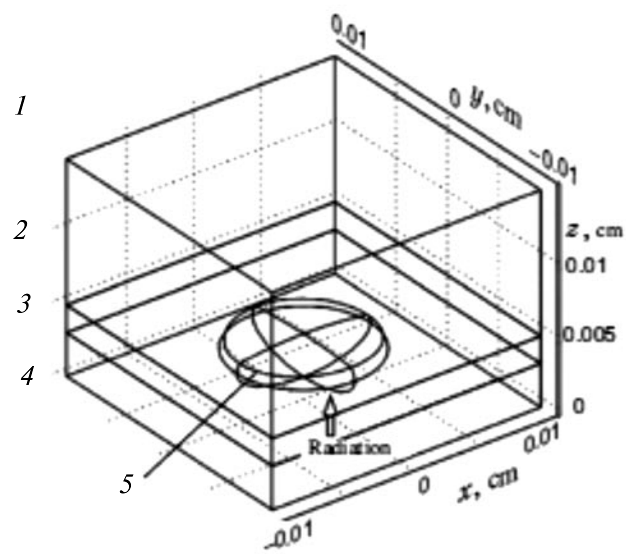

Fig. 2. Geometry of the medium used for calculations. Several layers of medium: *1* – stratum corneum, *2* – epidermis, *3* – dermis with a closed ingomogeneity (*5*), *4* – air

uniformly distributed within the interval [0, 2π]. Asymmetric scattering is not considered in this paper. Probability-density function p is constant and equals 1/2π [7].

After N photons are launched, we have a certain choice of statistical weights X_1, X_2, ..., X_n for each network node, obtained by the medium in its neighborhood. Statistical processing is carried out for these quantities. The most important ones are the mathematical expectation and the selective dispersion.

Let the weight of all N photons correspond to a certain energy q. Then, the mathematical expectation of the resulting weight by a network node is

$$\overline{X} = (1/n)\sum_{i=1}^{n} X_i, \quad (1)$$

where n is the number of absorptions in the neighborhood of the node of interest, and X_i is the statistical weight absorbed in the neighborhood of the i-th node of interest.

The mathematical expectation can be used to compute the energy density as follows:

$$Q = (\overline{X}q)/V, \quad (2)$$

where V is the volume of the neighborhood of the node of interest, and q is the energy that corresponds to the total statistical weight of N packets of photons.

The method called the implicit photon-capture technique is often used to take into account the absorption [8, 9]. The motion of a packet of photons, rather than of each photon separately, is considered in the modelling. A packet of photons models the motion of a set of photons along similar trajectories. Only some of the photons from a packet are absorbed when they interact with the medium, while the rest continue to move.

A cross-section in the xz plane was chosen for a graphical representation of radiation propagation in the medium. Fig. 3 shows the density distribution of the absorbed energy in this plane for 400-nm radiation.

For 800-nm radiation, the absorption coefficient is significantly less than the scattering coefficient, and a strongly scattering medium is modelled. Consequently, its penetration depth must be greater than in case when UV radiation is used. One more layer is therefore added to the region of calculation – the dermis, 0.05 cm thick. Fig. 4 shows the density distribution of the absorbed energy in the xz plane for radiation with wavelength 800 nm.

The character of the interaction of laser radiation with biological tissue depends on the absorption coefficient for this wavelength. Absorption predominates in the UV region; therefore, the contribution of scattering is

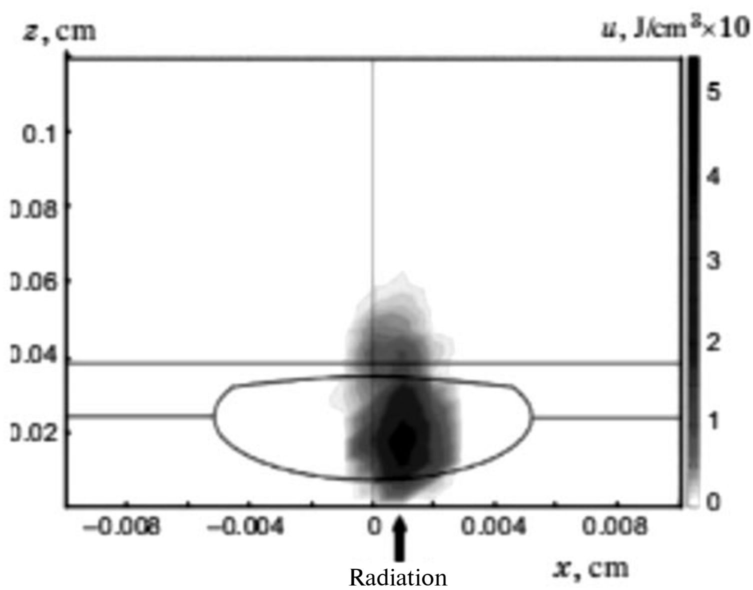

Fig. 3. Density distribution of absorbed energy u in the cross-sectional xz plane for a wavelength of 400 nm

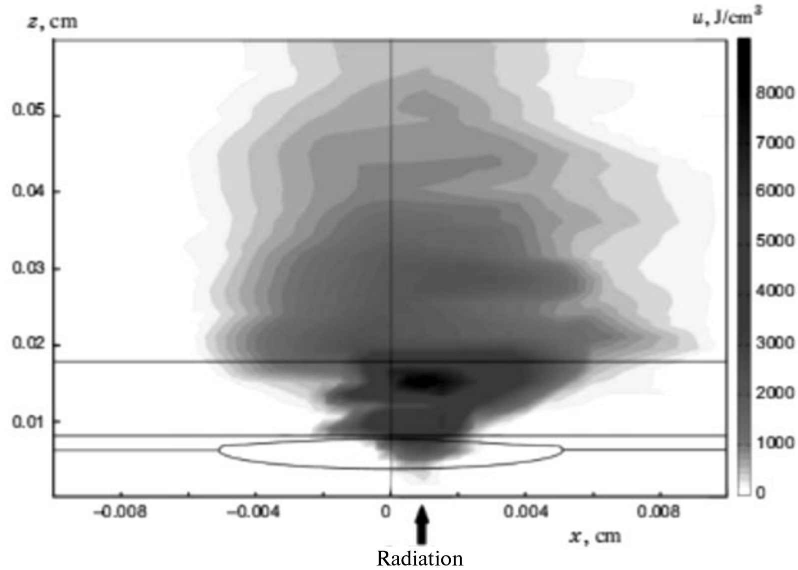

Fig. 4. Density distribution of absorbed energy u in the cross-sectional xz plane for a wavelength of 800 nm

fairly small, and the radiation penetration into the medium is just as shallow. For radiation from 600 to 1500 nm – the so-called terahertz window – in the event that scattering predominates over absorption, and the radiation-penetration depth is significantly greater than that for the UV region.

The laser radiation has the same power and energy in both cases. The penetration depth of UV radiation is slight. Therefore, a great part of the energy will be absorbed in a small volume near skin surface for 400-nm radiation, and the absorbed energy density is significantly greater than in the case of the wavelength of 800 nm [10].

IV. Conclusion

The paper concerns the propagation of optical radiation of different spectral regions in biological tissues. Monte Carlo method has been used in the study. We can simulate all the aspects of biological medium geometry using as the computational domain a grid of tetrahedron elements for 3D modeling or triangles in case of two dimensions. The modeling results give a visual representation of the absorbed energy density distribution in a biological medium. In case of one million packets of photons computational error does not exceed 1 %.

The proposed method is very flexible and well adaptable to the environments of different geometry. It allows obtaining two- and three-dimensional information on the distribution of light in tissue. The algorithms based on MC method can be applied both to diagnosing structural changes in the biological tissue of any closed geometry, and to calculating the temperature field and the boundaries of degradation during laser therapy.

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