Monte Carlo simulation of optical coherence tomography signal of the skin nevus

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Abstract. Monte Carlo (MC) numerical simulation of light propagation in living tissue is widely used for characterization of optical coherence tomography (OCT) signals. Using MC simulation we obtained OCT images of skin with dysplastic nevus. Two various positions of skin nevus in depth were considered. Comparing these OCT simulation results with image of skin without nevus, we showed that OCT medical approach allows to detect dysplastic nevus at different stages of its life.

1. Introduction

The optical coherent tomography (OCT) is one of the widely used and promising noninvasive technique of reconstruction of the medium internal structure. The research process of the internal structure is of great importance for such areas of science and technology as biomedicine [1–9], materials science [10] and diagnosis of art objects [11].

One of the most important applications of OCT in the biomedicine is to visualize the internal structure of the skin layers [4–6, 8, 9, 12], which is crucial for the early diagnosis of the skin cancer. The resulting OCT images has a high resolution. However, the skin is a strongly scattering medium, therefore, the depth of imaging is limited by the contribution of multiple scattering. So it is necessary to analyze the influence of the multiple scattering.

The process of light propagation in multiply scattering media is described by the theory of radiation transfer. The theory is based on radiative transfer equation. Since the solution of this equation by analytical methods is rather difficult, methods of numerical simulation are actively used. Numerical methods such as the Monte Carlo (MC) approach are typically employed [13–21]. MC simulation allows to classify the photons forming the OCT image and to assess their contribution to resulting OCT signal.

Various models of biological objects and algorithms were developed for MC simulation of OCT signal [12, 15, 16]. These algorithms are based on the classical model of the scattering medium, which is characterized by such parameters as absorption and scattering coefficients, anisotropy factor, and refractive index. The versatility of these algorithms allows applying MC approach for simulation of radiation propagation in layered media with known optical parameters.


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In the present paper, we consider the MC-based technique used for simulation of 2D OCT images of skin-like model with dysplastic nevus. Determination of skin nevus and its transformation in time is important for early diagnosis of skin cancer. OCT may become an effective instrument for such diagnosis. Using MC simulation we show the potential of OCT to distinguish different position of nevus.

2. Basic principles and algorithm of MC simulation

MC method allows realizing the consistent simulation of N photons trajectories in a scattering medium with subsequent statistical averaging of results.

Process of MC simulation consists of the following steps: (i) launching the photon in the medium, (ii) computation of the photon path-length, (iii) selection of the scattering direction, (iv) identification of reflection/refraction event at the medium boundaries, (v) definition of the detection and calculation the absorption [17]. The photon is injected in the medium according to the light source location and characteristics. The photon path-length between the points of collisions is defined by the equation [17]:

$$\Delta s = -ln(rand)/\mu_s, \tag{1}$$

where μ_s is the coefficient of scattering.

Direction of the photon after collision with the particle is determined by the scattering phase function. Angular distribution of Henyey-Greenstein phase function [22] is commonly used for MC simulation of light propagation in biological objects:

$$\chi(\theta) = \frac{1-g^2}{(1+g^2-2gcos(\theta))^{3/2}}, \tag{2}$$

where θ is the polar scattering angle. This phase function is characterized by an anisotropy factor g, which is equal to the mean cosine of the scattering angle. In case of crossing of layer borders, the angle of refraction β will be calculated using the Snell's law:

$$n_i sin(\alpha) = n_{i+1} sin(\beta), \tag{3}$$

where n_i, n_{i+1} are refraction indexes of layers, α is the incident angle. Fresnel law is used to derive a general expression for the reflection coefficient [17]:

$$R = 0.5\left(\frac{sin^2(\alpha-\beta)}{sin^2(\alpha+\beta)} + \frac{tg^2(\alpha-\beta)}{tg^2(\alpha+\beta)}\right). \tag{4}$$

Random number $\xi \in [0,1]$ is generated. If $\xi \leq R$ then photon is reflected. If $\xi > R$ then photon transmits. After that, the new position of the collision point is calculated. Every step repeats until the photon arrives at the plane of detector or absorbs in the medium. We used the total number of trajectory equal to 10^7.

The method of OCT is based on the principles of coherence interferometry. OCT approach allows recovering the optical properties distribution of the investigated sample depending on depth using the interference pattern. The interference pattern obtained by interference of the back scattered radiation and the reference radiation reflected from the Michelson interferometer mirror, located in the reference arm.

Neglecting speckle noise, OCT signal model is obtained from distribution of detected photons using the equation 5 [12]:

$$I(z) = I_0 \sum_{i=1}^{N} \sqrt{(W_i)} exp\left[-\left(\frac{2z-L_i}{l_c}\right)^2\right], \tag{5}$$

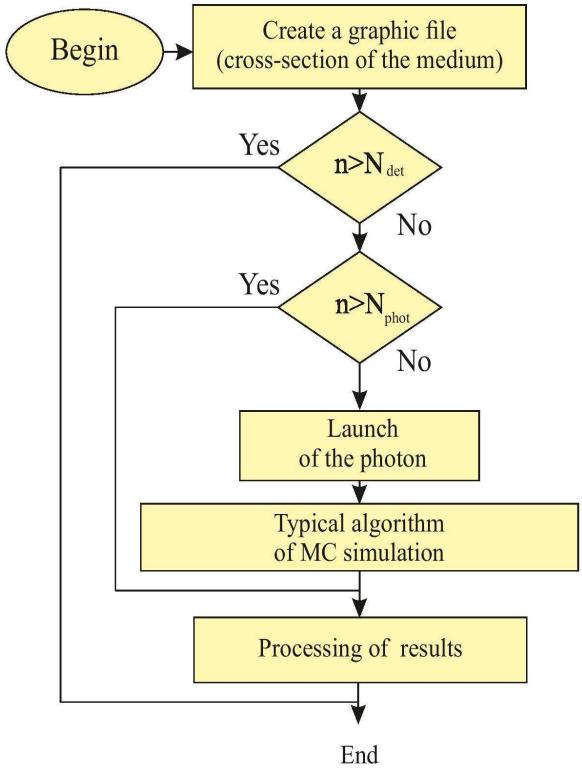


Figure 1. Algorithm of MC simulation of OCT images.

where N is the number of trajectories, l_c is the coherence length of the light source, I_0 is the constant, which defines properties of interferometer, W_i is the weight of $i-th$ photon, $2z$ is the optical path length in the reference arm, and L_i is the optical path length. Simulation algorithm is presented in the figure 1.

3. Models of skin with and without nevus

Using the described above MC numerical approach for OCT simulation, we analyzed the OCT imaging in presence or absence of the nevus in the skin. We considered one case without nevus (figure 2(a)) and two cases of different nevus location: in the derma (figure 2(b)) and in the board between derma and epidermis (figure 2(c)).

We used the model of human skin with four non-flat layers [12]. The glass plate with thickness of 1.5 mm was chosen as the first layer. For simplicity of the numerical computations, the two-dimensional model of scattering medium was used. In the source location point the incident photon is injected orthogonally onto the first layer. Optical parameters (refractive index n, scattering coefficient μ_s, absorption coefficient μ_a, and anisotropy factor g) and position of every layer are shown in the figure 2(a). Optical parameters and nevus position for two cases are shown in the figures 2b,2c. We used the optical parameters of the skin layers, which can be found in literature [12, 23]. Parameters of MC simulation are shown in the table 1.

Table 1. Parameters of MC simulation.

Case	a	b	c
Number of photons, m	50	50	100
Wavelength, nm	910	910	910
Coherence length, μm	10	10	10
Thickness of the nevus, μm	-	60	60
Penetration depth of the nevus in the skin, mm	-	0.23	0.35

4. Results

The results of OCT simulation using MC approach for the considered cases are shown in the figures 2(d–f). The layers boundaries in the figures 2(d–f) are clearly seen. In the case where the nevus is located in the deep of the dermis (figure 2(b)), the border of nevus (figure 2(d)) is not as clear as the boundaries of layers because of strongly scattering properties of nevus material. In the case where the nevus is located between dermis and epidermis (figure 2c),

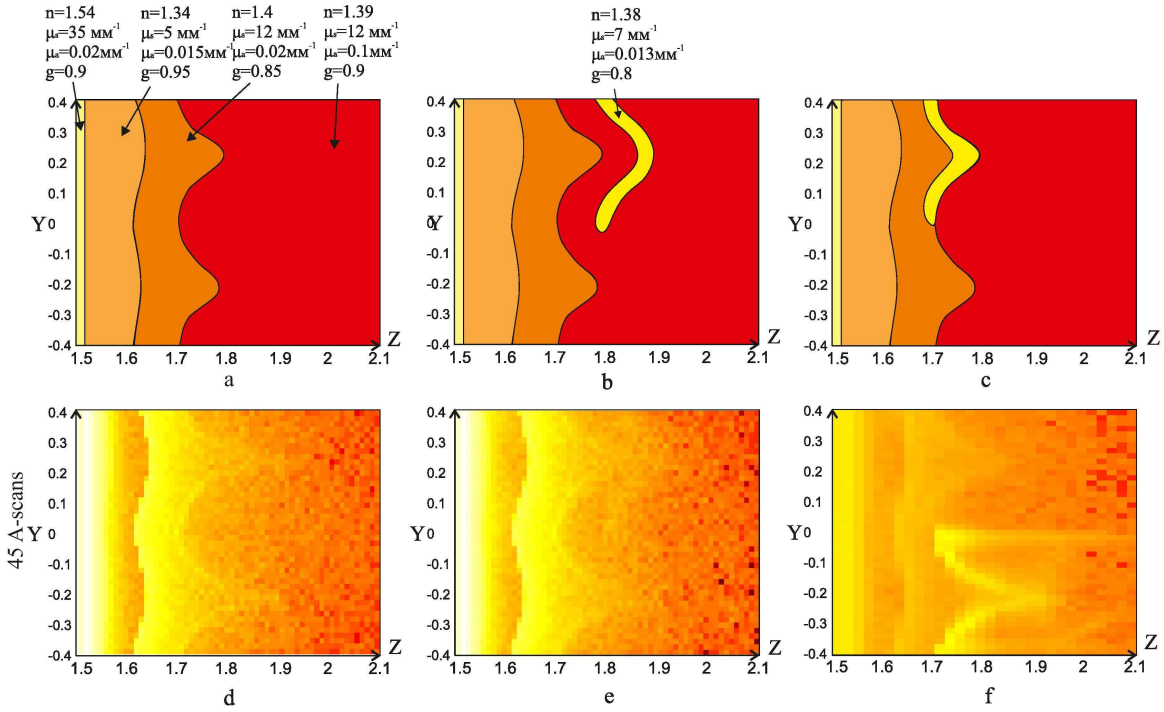


Figure 2. 2D models of skin and results of OCT simulation for the corresponding models. Panels (a) and (d) demonstrate model and result for the skin without nevus, panels (b) and (e) – for nevus in derma layer, panels (c) and (f) – for nevus in epidermis layer.

the border of nevus and border, where nevus is located, disappear (figure 2(d)). Thus, nevus has enlightenment properties. The differences of OCT images for two nevus locations approve potential scope of OCT for nevus deformation and early diagnosis of skin diseases. Such results can be used for further development of diagnosis criteria in OCT analysis of skin.

5. Conclusion

In this work Monte Carlo simulation approach of optical coherence tomography of human skin with dysplastic nevus was described. To determine the diagnostic capability of OCT for different stages of nevus life we considered three types of skin tissue media: the skin without the nevus, the skin with dysplastic nevus in the dermis, and the skin with dysplastic nevus on the border between the dermis and epidermis. The analysis of the results showed the following:

- detection of the nevus within the layer is possible without using additional image processing;
- nevus scatters has strong scattering properties;
- nevus has and enlightenment properties when placed on the interface between two layers.

These obtained results approved the possibility of nevus diagnosis and provided the further definition of the necessary criteria for OCT analysis of skin cancer.

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References

[1] Schmitt J 1999 *Selected Topics in Quantum Electronics, IEEE Journal of* **5** 1205–1215
[2] Ourutina M N, Gladkova N D, Feldchtein F I, Gelikonov G V, Gelikonov V M, Kuranov R V and Sergeev A M 1999 *Proc. SPIE* **3567** 97–107
[3] Zaytsev K I, Kudrin K G, Chernomyrdin N V, Khorokhorov A M, Prytov A B, Dolganova I N, Perchik A V, Reshetov I V and Yurchenko S O 2015 *Journal of Physics: Conference Series* **584** 012013
[4] Gambichler T, Moussa G, Sand M, Sand D, Altmeyer P and Hoffmann K 2005 *Journal of dermatological science* **40** 85–94
[5] Veksler B A, Kuz'min V L, Kobzev E D and Meglinski I V 2012 *Quantum Electronics* **42** 394–398
[6] Mogensen M, Thrane L, Jrgensen T M, Andersen P E and Jemec G B E 2009 *Journal of Biophotonics* **2** 442–451
[7] Kirillin M Y, Priezzhev A V, Tuchin V V, Wang R K and Myllyl R 2005 *Journal of Physics D: Applied Physics* **38** 2582–2589
[8] Hee M R, Izatt J A, Swanson E A, Huang D, Schuman J S, Lin C P, Puliafito C A and Fujimoto J G 1995 *Archives of Ophthalmology* **113** 325–332
[9] Kirillin M Y, Bykov A V, Priezzhev A V and Myllyl R 2008 *Quantum Electronics* **38** 486
[10] Alarousu E, Gurov I and ang R Myllyla andA Zakharov J H 2003 *Proc. SPIE* **5149** 13–20
[11] Arecchi T, Bellini M, Corsi C, Fontana R, Materazzi M, Pezzati L and Tortora A 2006 *Optics and Spectroscopy* **101** 23–26
[12] Kirillin M, Meglinski I, Kuzmin V, Sergeeva E and Myllylä R 2010 *Opt. Express* **18** 21714–21724
[13] Subramanian H, Pradhan P, Kim Y L, Liu Y, Li X and Backman V 2006 *Appl. Opt.* **45** 6292–6300
[14] Karamata B, Lambelet P, Laubscher M, Leutenegger M, Bourquin S and Lasser T 2005 *J. Opt. Soc. Am. A* **22** 1369–1379
[15] Yao G and Wang L V 1999 *Physics in Medicine and Biology* **44** 2307
[16] Zhu C and Liu Q 2013 *Journal of Biomedical Optics* **18** 050902–050902
[17] Wang L, Jacques S L and Zheng L 1995 *Computer Methods and Programs in Biomedicine* **47** 131 – 146
[18] Doronin A, Radosevich A J, Backman V and Meglinski I 2014 *J. Opt. Soc. Am. A* **31** 2394–2400
[19] Lu Q, Gan X, Gu M and Luo Q 2004 *Applied Optics* **43** 1628–1637
[20] Gangnus S V, Matcher S J and Meglinski I V 2004 *Laser Physics* **14** 886–891
[21] Shlivko I L, Kirillin M Y, Donchenko E V, Ellinsky D O, Garanina O E, Neznakhina M S, Agrba P D and Kamensky V A 2015 *Skin Research and Technology* **21** 419–425
[22] Henyey L G and Greenstein J L *Astrophys. J.* **93** 70
[23] Garcia-Uribe A, Zou J, Duvic M, Cho-Vega J, Prieto V and Wang L 2012 *Cancer Res.* **72** 2738–2745