MONTE CARLO CALCULATION OF ENERGY STRAIN ON A MUSCLE FIBER DUE TO LIGHT ABSORBPTION

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Abstract: Monte Carlo models of light propagation in different materials are widely used in today's science. In this paper the model is applied to a optically non-linear theoretical sample of a muscle fiber to determine the behavior of a photon inside the tissue, the energy absorbed by the sample and matching the energy strain to a possible effect on the fiber.

Keywords: Monte Carlo, photon absorption, light propagation, biological tissue, muscle fiber

1. INTRODUCTION

The Monte Carlo (MC) method is a technique of simulating physical processes using a stochastic model [1]. This method finds use in physics for simulation of systems with many degrees of freedom, in economics for risk and business calculation, or in mathematics for multidimensional definite integral evaluation. There are many models and algorithms created for exploration of a behavior of distinct problem classes, but so far, only a small part of them deal with anisotropic systems, like biological tissue, multiple scattering and internal light reflection [2].

For this simulation and further energy strain calculation, a theoretical bovine striated muscle fiber segment was created, and the photon histories of scattering, absorption and internal reflection were simulated. The photons are not polarized, and it is therefore not required for us to take into account the change in polarization with increasing optical thickness of the medium, or the impact of the polarization on the light propagation [3].

The effects of laser light on tissue can be separated into three basic groups affecting different levels of biological structure. During photochemical effect, the energy of laser disrupts chemical bonds on a molecular level, photothermal effect increases the temperature of the sample, causing possible cellular changes and damage and photomechanical effect causes mechanical changes on the highest level of biological structure.

2. MONTE CARLO MODEL

The algorithm used for this simulation is based upon a general steady-state light transport model [4]. It was created in MATLAB, and is heavily focused on the propagation of photons in a singular muscle fiber. The behavior of photon in any other layers of tissue surrounding the muscle fiber in question after their exit from the observed area is not included in the model.

2.1. PHOTON INITIATION, MOVEMENT AND TERMINATION

In MATLAB, the position of a photon in any given time is given in cartesian coordinate system. The starting position is selected as the point of entry into the tissue, (x, y, z = 0), with an initial direction orthogonal to the x and y axes, and a weight of 1, which is used to observe the energy changes due to the absorption and reflection in the tissue during the course of the program. In the moment of the entry, a specular reflectance R_{sp} on the surface will occur:

$$R_{sp} = \frac{(n_1-n_2)^2}{(n_1+n_2)^2} \tag{1}$$

where n_1 is the refractive index of the surrounding (air or tissue), and $n_2$is the refractive index of the observed medium (muscle fiber).

In the same time, the weight of the photon is reduced by the value of R_{sp}.

After the entry of the photon into the observed medium, and in each subsequent repeated step of the algorithm, a step size is calculated:

$$step = \frac{-log(rand)}{\mu_t} \tag{2}$$

where $rand$ is a random number from the (0,1) interval, and is separately generated for each step calculation, and μ_t is an extinction coefficient, calculated as a sum of absorption and scattering coefficient of the medium. If the step was not enough for the photon to reach boundary, the photon will undergo absorption and scattering. Otherwise reflection or transmission at boundary will occur.

Photon is terminated if it is moved outside of the medium during a step, or if the weight of the photon reaches a predefined threshold, signaling a total absorption in the tissue.

2.2. PHOTON SCATTERING AND ABSORPTION

During each step, the photon inside the tissue undergoes scattering and absorption. The scattering event provides us with new direction to move the photon:

$$\overline{x'} = \frac{\sin\theta}{\sqrt{1-\bar{z}^2}}(\bar{x}\bar{z}\cos\psi - \bar{y}\sin\psi) + \bar{x}\cos\theta$$
$$\overline{y'} = \frac{\sin\theta}{\sqrt{1-\bar{z}^2}}(\bar{y}\bar{z}\cos\psi - \bar{x}\sin\psi) + \bar{y}\cos\theta$$
$$\overline{z'} = -\sin\theta\cos\psi\sqrt{1-\bar{z}^2} + \bar{z}\cos\theta \tag{3}$$

where $\bar{x}$ is the old direction on the x axis, $\overline{x'}$is the new one, θ is the deflection angle [0,π) and ψ is the azimuth [0,2π).

Absorption in each step causes a weight loss in the photon, defined by:

$$\Delta W = W\frac{\mu_a}{\mu_t}. \tag{4}$$

2.3. BOUNDARY INTERACTION

In the case of photon hitting the boundary, the program decides, whether the photon escapes the medium, or internal reflection occurs. The internal reflectance $R(a_i)$ is calculated by Fresnel's formula:

$$R(a_i) = \frac{1}{2}\left[\frac{sin^2(a_i-a_t)}{sin^2(a_i+a_t)} + \frac{tan^2(a_i-a_t)}{tan^2(a_i+a_t)}\right] \tag{5}$$

where a_i is the angle of incidence, and a_t is the angle of transmission.

2.4. Model output

Optical properties of a theoretical distal muscle fiber for fine coordination with the width of 20 µm were chosen from literature [5]:

Number of photons	10000	**Refractive index of the surrounding**	1,3
Absorption coefficient	0,74 cm^{-1}	**Refractive index of the medium**	1,38
Scattering coefficient	140 cm^{-1}	**Scattering anisotropy**	0,96

Table 1: Optical properties entering the simulation

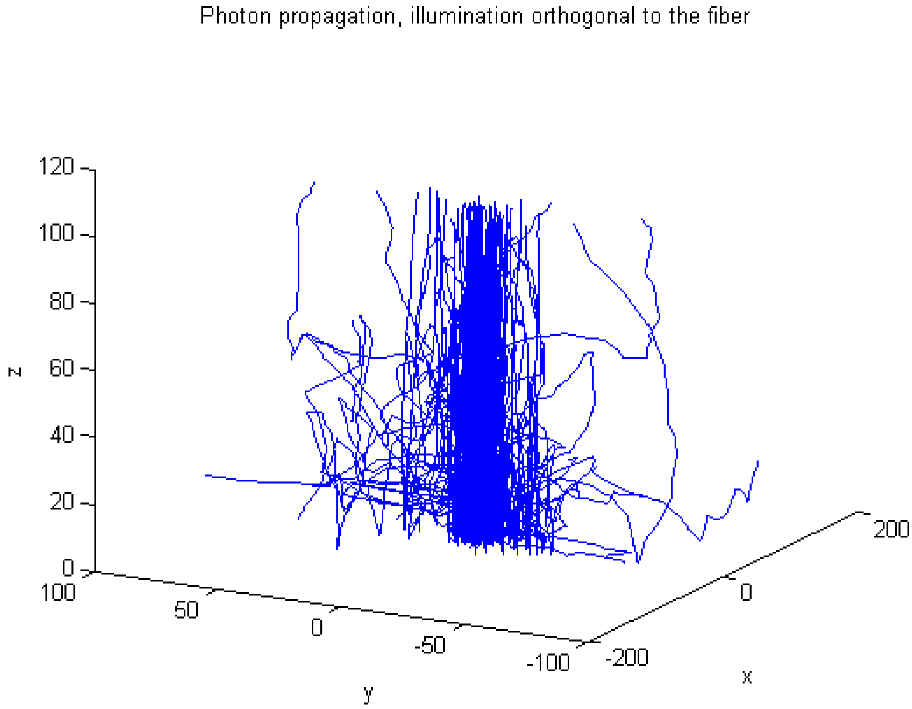

Figure 1: Monte Carlo simulation of propagation of 100 photons through muscle fiber, perpendicular illumination with a unit of size 0,1 µm

For a perpendicular illumination setting of the simulation (Figure 1) the width of the sample plays a significant role, because the photon will be transmitted in majority of cases, therefore making the refractive indices of the medium and the surrounding material more important because of backscattering. The parallel illumination (Figure 2) variation emphasizes the propagation of photon in the fiber rather than interaction with the medium/surroudings junction, thus making the journey of each photon less eventful. The length of the fiber is greater than the diameter by five orders of magnitude, therefore making it for this case effectively infinite.

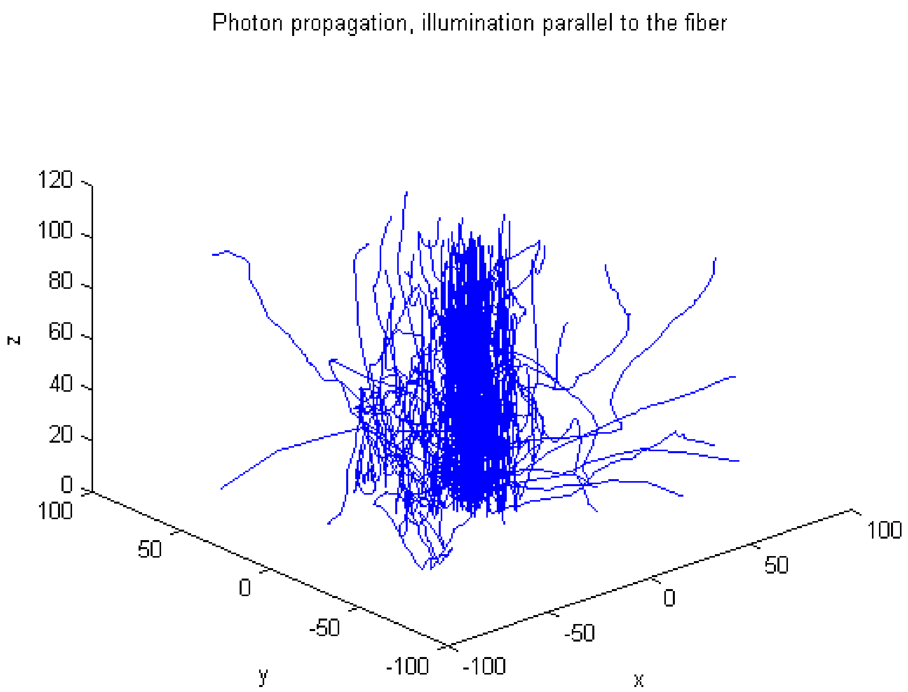

Figure 2: Monte Carlo simulation of propagation of 100 photons through muscle fiber, parallel illumination with a unit of size 0,1 μm

	Perpendicular	Parallel
Terminated photons	6848± 230	42 ± 12
Transmitted photons	33941 ± 1045	22571 ± 253
Photons on the boundary	59240 ± 4323	77387 ± 223
Absorption per photon	0,7294 ± 0,0035	0,5106 ± 0,0054

Table 2: Output of the simulation for illumination perpendicular and parallel to the fiber

3. ENERGY STRAIN CALCULATION

During the photon propagation through the muscle tissue, a certain amount of energy is absorbed, which can be calculated from the average absorption value of the tissue provided by the Monte Carlo simulation.

First, the energy of a single photon emitted by the laser is calculated:

$$E = \frac{h.c}{\lambda} = 3{,}143 \times 10^{-19}\mathrm{J} \qquad (6)$$

where h is Planck constant ($6{,}636 \times 10^{-34}\mathrm{J.s}$), c is the speed of light ($2{,}988 \times 10^{8}\mathrm{m/s}$), and λ is the wavelength of the laser used (here $632 \times 10^{-9}\mathrm{m}$).

A laser with the power P of 5mW then emits 1.591×10^{16} photons per second:

$$f = P.\lambda\ . \qquad (7)$$

For the perpencidular illumination of muscle fiber $2{,}4894 \times 10^{-19}$ Joules per photon is absorbed, which makes it a total of $3{,}9607 \times 10^{-3}$ Joules per second for the specified red laser. For parallel illumination it is $1{,}7427 \times 10^{-19}$ Joules per photon and $2{,}2772 \times 10^{-3}$ Joules per second absorbed.

The result of this amount of energy absorbed can be neglected in a living tissue when the laser beam illuminates the tissue for a period shorter than 80 seconds, because only minor alterations on cellular level occur, which can be repaired by a natural regeneration processes [6]. On an extracted sample, however, especially the photochemical and photothermal effects can lead to changes on a molecular level, affecting other measurements when illuminated with the laser of previously specified power and wavelength for longer than 120 seconds.

4. CONCLUSION

The Monte Carlo model described can be used for determinativ of the speed and magnitude of a photobleaching effect on an organic tissue during measurement. It yields sufficiently precise results for energy absorption per photon during propagation inside a muscle fiber for calculation of an energy strain affecting measurement results during laser light illumination of the sample. Heat dissipation, decay of sample in time because of natural chemical processes and further interactions with photon escaped from the sample are neglected for the reason of model simplification and universality.

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REFERENCES

[1] Robert, P. C., Casella, G.: Monte Carlo Statistical Methods, New York, Springer Science + Business Media New York 2004, ISBN 978-1-4419-1939-7.

[2] Wilson, B. C., Adam, G.: A Monte Carlo model for the absorption and flux distribution of light in tissue, Medical Physiology 1983, vol. 10, p. 824-830.

[3] Ambirajan, A., Look, D. C.: A backwards Monte Carlo study of the multiple scattering of a polarized laser beam, J. Quant. Spectrosc. Radiat. Transfer 1997, vol. 58, no. 2, p. 171-192.

[4] Wang, L., Jacques, S. L.: Monte Carlo Modeling of Light Transport in Mutli-layered Tissues in Standard C, Comput. Methods Programs Biomed. 1995, vol. 47, no. 2, p. 131-146.

[5] Bashkatov, A. N., Elina, A. G., Tuchin, V. V.: Optical properties of skin, subcutaneous, and muscle tissues: a review, Journal of Innovative Optical Health Sciences 2011, vol. 4, no. 1, p. 9-38, DOI: 10.1142/S1793545811001319.

[6] Thomsen, S.: Pathologic analysis of photothermal and photomechanical effects of laser-tissue interactions, Photochemistry and Photobiology 1991, vol. 53, issue 6, p. 825-835.