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RESEARCH OF OPTICAL PROPERTIES OF BIOTISSUE ON THE BASIS OF NUMERAL MODELING OF PHOTONS TRANSPORT

Rovira R.H.[a], Pavlov S.V.[b], Azarov O.D.[b], Kaminsky A.S[b]

[a]Universidad Estatal Península de Santa Elena, Avda. Principal La Libertad, Santa Elena, Ecuador;
[b]Vinnytsia National Technical University, 95 Khmelnitskoe shose, Vinnytsia, Ukraine, 21021

The research of subsurface structures of skin by means of optical radiation has significant advantages compared with other techniques. To evaluate these structures, all the existing methods depend on the backscattered photons from tissues. The analysis of the distribution of these photons over the skin and its relative intensity becomes extremely essential. In this article, we presented a simulation based on Monte Carlo Methods and the optical properties of the skin layers to evaluate the backscattered photons when the skin is irradiated with a narrow beam of laser light.

Keywords: *tissue imaging, Monte Carlo methods, scattering.*

Introduction

Over the last decade, biomedical optics has been of considerable interest among researchers [13, 14]. One of the tasks of biomedical optics is the development of diagnostic methods based on near-infrared (NIR) radiation. Optical imaging has some potential advantages over existing radiological techniques: its non-ionizing radiation allows repeated use without damaging the patient.

The high number of scattering events that occur when light propagates through tissues severely limits the ability to create images from the internal structures of the tissues. A review of methods used to improve the imaging capability is described in [4].

Photons, which have undergone few scattering events, contain most of the physiological information [3]. Unfortunately, the absorption coefficient is considerably less than the scattering coefficient so that the measured signals at distances of a few millimeters or more are dominated by diffused light. The subject of much of the experimental research focuses on identifying and measuring the minimally scattered photons.

Analysis of methods

The radiative transfer theory.

The most popular model for photon propagation is the theory of radiative transfer. This model can be regarded as the interaction between photons and particles embedded in the medium, in which photons propagate. It is derived by considering energy balance of the incoming, outgoing, absorbed and emitted flow within an infinitesimal volume [7, 10].

$$\frac{1}{c}\cdot\frac{\partial I_\lambda(x,\Omega)}{\partial t}+\nabla(I_\lambda(x,\Omega)\cdot\Omega)= =-W_\lambda^{abs}(x,\Omega)-W_\lambda^{out-s}(x,\Omega)- -W_\lambda^{em}(x,\Omega)+W_\lambda^{in-s}(x,\Omega) \quad \text{Eq.1}$$

A beam of light loses energy by absorption in the infinitesimal volume and by out scattered photons from the volume. This equation can be simplified assuming that the radiation field is at steady state condition, incorporating models for absorption and scattering and neglecting emission.

The scattering of photons is determined by the phase function, *P(cos*θ), which specifies the probability of deviation from incident direction in an angle *θ*. The average dispersion, known as the asymmetry parameter *g*, varies between -1 and 1. It is considered that after a number of scattering events corresponding to *1/(1-g)* the direction of the photon is totally random and independent of the incident angle.

The radiative transport equation has six independent variables (x, y, z, θ, ψ, and t). It is extremely difficult to solve analytically, rational approximations and statistical approaches must be chosen, depending on absorption scattering relation. A numerical approach to the transport equation is based on Monte Carlo simulations.

The Monte Carlo Methods

The Monte Carlo method uses the probability distributions of the optical parameters of the medium to simulate random paths of each photon. The use of Monte Carlo techniques in photon transport modeling has increased dramatically in the last few years [5, 6, 11, 12]. The algorithm is based on the following assumptions: a beam of light incidents normally to the surface of the outermost layer of the skin. In the interaction with the layer, the photons of the beam might be reflected at the layer, elastically scattered, absorbed or pass through the layer. The path length between two scattering events λ is calculated from a logarithmic distribution equation 2.

$$\lambda = \frac{-\ln(\xi)}{(\mu_s + \mu_a)} \qquad \text{Eq. 2}$$

The scattering direction is taken from two angles: the angle of deviation from the photon trajectory θ and the azimuthal angle ψ. The scattering angle θ is taken from the Henyey and Greenstein distribution, while ψ takes a random value between 0 and 2π. After experiment a scattering event the weight of the photon is updated according to Lambert's law. If the remainder weight is greater than a minimum value and the photon is within the boundaries the process is repeated.

The skin model

Human skin is composed of two layers: the epidermis and the dermis. The epidermis is the outermost layer of the skin. Its thickness is about 0,2 mm on average, and it varies depending on location on the body. Furthermore, the thickness also depends on to the volume of water that epidermis holds. The epidermis is further divided into five sub layers: stratum corneum, stratum lucidum, stratum granulosum, stratum spinosum and the stratum basale. This layer does not contain veins and capillaries.

The stratum corneum is the outer sub layer of the epidermis, its thickness ranges from 8-15 micrometers. This sub layer is composed of several layers of hexagonal shaped flattened hard cells named horny cells or corneocytes. Corneocytes are dry dead cells without organelles, filled with keratin fibers. Stratum corneum prevents excessive dehydration of the skin.

The dermis lies beneath the epidermis. It is much thicker than the epidermis usually its thickness ranges from 1 to 4 mm. The main components of the dermis are collagen and elastin fibers. Compared to the epidermis, there are much fewer cells and much more fibers in the dermis. Dermis has two sub layers: the papillary dermis and the reticular dermis. The papillary dermis is a loosely connected tissue and includes a large amount of nerves fibers that form an intricate network. The reticular layer is the bottom sub layer of the dermis. It is a transition to the sub cutis. This sub layer has a thicker network than the papillary and includes fewer nerve fibers and capillaries. In this sub layer, collagen fibers are aggregated into thick bundles, which are typically parallel to the surface of the skin.

Skin optical properties: refractive index, scattering coefficient, absorption coefficient affect light tissue interaction. Different concentration of blood, melanin, and keratin give skin layers optical properties, [1, 2, 8, 9]. In the skin, lipids and proteins scatter incoming light. Stratum corneum contains mainly lipid scatterers. Scattering is more intense for those objects, whose size is close to the wavelength of the incoming light. The primary protein scatterers in the skin are keratins and melanin in the epidermis, and collagen and elastin fibers in the dermis.

Skin has three main absorbers: blood, melanosomes, and keratin. Blood vessels and capillaries are found only below the epidermis. The main blood absorption bands are between 400 and 425 nm and 500 and 600 nm. At wavelengths longer than 600 nm the blood absorption is remarkably low. The melanosome concentration strongly affects the skin reflectance, especially for the range of wavelengths within 300-700 nm, but less at the shortest UVB wavelengths. Keratin is a main component of the epidermis and, in particular, of the stratum corneum. Keratin almost exclusively

Table 1

Skin optical properties

Layer	Thickness δ [cm]	n	Abs. Coeff. μ_a [cm^{-1}]	Scat. Coeff. μ_s [cm^{-1}]	Anisotropy g
S. Corneum	0,002	1,562	0,0022	251	0,90
Epidermis	0,009	1,529	32,0000	321	0,81
P. Dermis	0,020	1,493	0,1100	132	0,82
R. Dermis	0,180	1,488	0,0806	132	0,82
Hypodermis	0,300	1,567	1,1000	118	0,90

absorbs UV radiation with a peak at approximately 280 nm. The optical properties of the skin layer are summarized at table 1.

Photon propagation modeling

The algorithm for the photon transport was implemented in Matlab. We evaluated the reflectance - transmittance characteristic at the air – stratum corneum interface for the optimal selection of the incident angle figure 1.

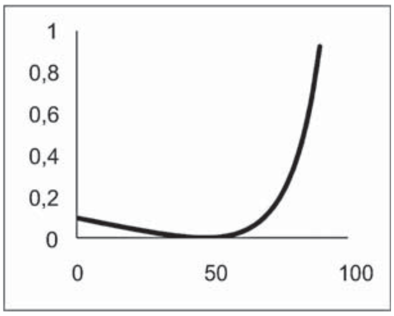

Figure 1. Fresnel reflectance at air – stratum corneum interface

We evaluated the interaction of photons with each layer by comparing the random free path length λ with the respective thickness figure 2. The distribution $P(cos\theta)$ was calculated in each layer to evaluate the backscattering probability. The simulation was executed to evaluate the percentage of backscattering photons from each layer. We considered the hypodermis as a fully diffuse reflector.

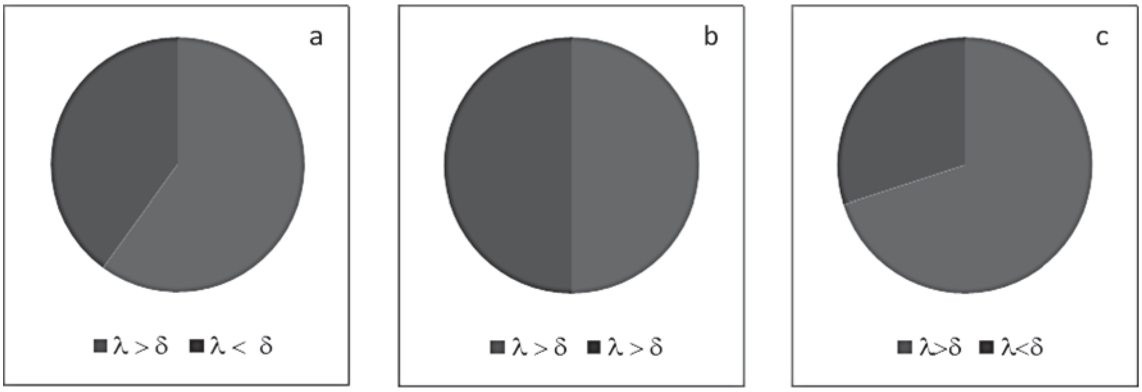

Figure 2. Free path length: a) Stratum corneum, b) Epidermis, c) Papillary dermis

The simulation was executed for a set of photons. The projection at plane X-Z of the trajectory was plotted. The intersection of the backscattered photons with the stratum corneum-air interface was plotted as well figures 3 and 4.

The relative backscattered intensity was evaluated assuming a narrow beam from a pointer laser. The relative intensity was taken as the quotient between the photon densities of the incident beam to the backscattered light figure5.

Results

The highest value of transmittance at the air stratum corneum interface is at 450. At a first thought, it seems advisable to direct the light beam at this angle, but as the incident angle increases the number of backscattered photons from the stratum corneum decreases without reaching inner structures. The stratum corneum seems to be transparent for NIR photons since 60% pass through this layer without been neither scattered nor absorbed. In the epidermis, the probability of scattering is greater. According to the simulation 50% of the photons are scattered. Forward scattering is predominant for both stratum corneum and epidermis. All the photons that pass to the reticular dermis are sooner or later scattered or absorbed since λ in all the simulations were less than the thickness of the layer. As one can see in figure 5, the relative intensity decreases rapidly as the points is further from the point of incidence.

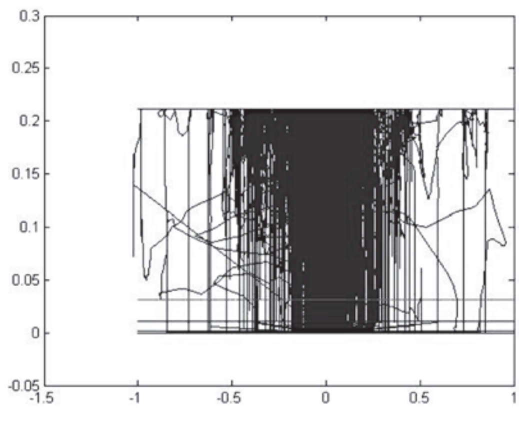

Figure 3. Simulation of photon transport through skin layers

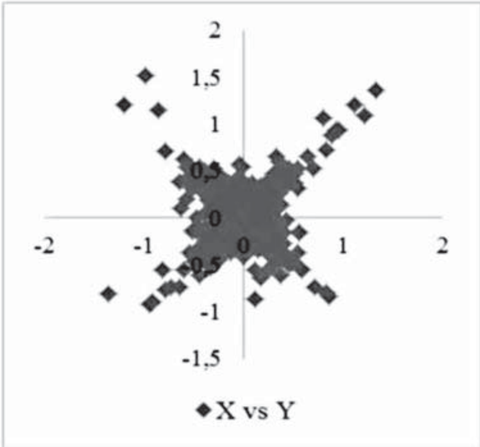

Figure 4.Distribution of backscattered photons at skin surface. Horizontal axis in cm

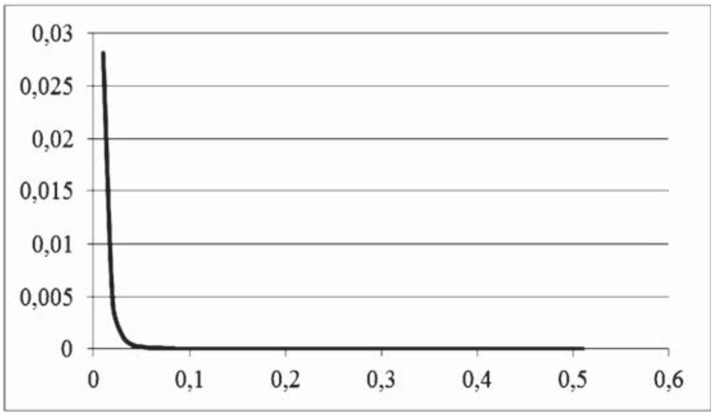

Figure 5. Relative intensity of backscattered photons at skin surface. Horizontal axis in cm

Summary and future research

We have simulated the photon trajectories through skin layers to estimate the backscattered fraction of the incident light, its distribution over the skin and its relative intensity. This work allows estimating photo detector placement in research of the internal structure of the skin. It would be interesting to consider the impact of scattering on polarization for imaging polarimetry of tissues.

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ИССЛЕДОВАНИЕ ОПТИЧЕСКИХ СВОЙСТВ БИОТКАНИ НА ОСНОВЕ ЧИСЛЕННОГО МОДЕЛИРОВАНИЯ ТРАНСПОРТА ФОТОНОВ

[а]Ровира Х.Р., [б]Павлов С.В., Азаров О.Д., Каминский А.С.
[а]Государственный университет «Пенинсула де Санта Елена», Эквадор
[б]Винницкий национальный технический университет,
Хмельницкое шоссе, 95, г.Винница, Украина, 21021

Исследование внутренней структуры кожи с помощью оптического излучения имеет значительные преимущества по сравнению с другими методами. Существующие методы для оценки этих структур базируются на моделировании транспорта фотонов в рассеивающей среде. Поэтому анализ задачи моделирования распространения фотонов и определения относительной интенсивности по поверхности кожи становится актуальным. В этой статье представлены результаты статистического моделирования на основе методов Монте-Карло оптических свойств биоткани посредством оценки отраженных фотонов при облучении кожи узким пучком лазерного излучения.

Ключевые слова: *визуализация, метод Монте Карло, рассеяние.*

ДОСЛІДЖЕННЯ ОПТИЧНИХ ВЛАСТИВОСТЕЙ БІОТКАНИНИ НА ОСНОВІ ЧИСЕЛЬНОГО МОДЕЛЮВАННЯ ТРАНСПОРТУ ФОТОНІВ

[а]Ровіра Х.Р., [б]Павлов С.В., Азаров О.Д., Камінський А.С.
[а]Державний університет «Пенінсула де Санта Елена», Еквадор
[б]Вінницький національний технічний університет,
Хмільницьке шосе, 95, м.Вінниця, Україна, 21021

Дослідження внутрішньої структури шкіри за допомогою оптичного випромінювання має значні переваги порівняно з іншими методами. Існуючі методи для оцінювання цих структур базуються на моделюванні транспорту фотонів у розсіювальному середовищі. Тому аналіз задачі моделювання розподілу фотонів та визначення відносної інтенсивності по поверхні шкіри є актуальним. У даній статті представлено результати статичного моделювання на основі методів Монте-Карло і оптичних властивостей біотканини шляхом оцінювання фотонів, які відбиваються при опроміненні шкіри вузьким пучком лазерного випромінювання.

Ключові слова: *візуалізація, метод Монте Карло, розсіювання.*