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Light source distribution and scattering phase function influence light transport in diffuse multi-layered media

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ABSTRACT

Red and near-Infrared light is often used as a useful diagnostic and imaging probe for highly scattering media such as biological tissues, fruits and vegetables. Part of diffusively reflected light gives interesting information related to the tissue subsurface, whereas light recorded at further distances may probe deeper into the interrogated turbid tissues. However, modelling diffusive events occurring at short source-detector distances requires to consider both the distribution of the light sources and the scattering phase functions. In this report, a modified Monte Carlo model is used to compute light transport in curved and multi-layered tissue samples which are covered with a thin and highly diffusing tissue layer. Different light source distributions (ballistic, diffuse or Lambertian) are tested with specific scattering phase functions (modified or not modified Henyey-Greenstein, Gegenbauer and Mie) to compute the amount of backscattered and transmitted light in apple and human skin structures. Comparisons between simulation results and experiments carried out with a multi-spectral imaging setup confirm the soundness of the theoretical strategy and may explain the role of the skin on light transport in whole and half-cut apples. Other computational results show that a Lambertian source distribution combined with a Henyey-Greenstein phase function provides a higher photon density in the stratum corneum than in the upper dermis layer. Furthermore, it is also shown that the scattering phase function may affect the shape and the magnitude of the Bidirectional Reflectance Distribution (BRDF) exhibited at the skin surface.

1. Introduction

Investigations on light-tissue interaction processes have been performed owing to multiple applications related to therapy and diagnosis in the medical field [1–4]. The rendering of object with computer graphics has been also improved with a better knowledge on the mechanisms of light propagation in turbid media [5]. Furthermore, the interest has been focused on the quality prospect of fruits and vegetables using diffusion models and non-invasive optical spectroscopy systems [6]. The use of red and near-infrared (NIR) light especially allows to probe deeply into interrogated turbid tissues [7], showing the possibility to extract spectral information on tissue constituents. In this wavelength range, several key optical parameters characterize the light propagation in turbid media [1]: the average refractive index (n_r), the absorption coefficient (μ_a), the scattering coefficient (μ_s), and the scattering phase function ($p(\theta)$). The absorption coefficient μ_a and scattering coefficient μ_s are respectively the number of absorption and scattering events per unit length, while the phase function $p(\theta)$ represents the angular distribution of a scattering event. When the diffusion is predominant [8], the so-called reduced scattering coefficient defined as $\mu'_s=\mu_s(1-g)$ is useful, where g (anisotropy factor) is the average cosine of the angular deviation. This leads to the fact that the transport length $1/\mu'_s$ describes the distance which light travels before the propagation direction be completely randomized due to scattering events. However, a rigorous treatment of the light propagation in turbid tissues requires to use the radiative transfer equation (RTE) still considering μ_a, μ_s and $p(\theta)$ [9]. Note that an exact solution of the RTE is difficult to find [10], notably due to the integro-differential form of this equation and regarding all the constraints related to the tissues (heterogeneities, structure, complex boundaries, and source-detector arrangements).

A usual way to solve the RTE is to use Monte Carlo (MC) method [11], which has the advantage to follow the photon paths according to probability functions. These probabilities estimate length of free paths, direction changes, absorption and Fresnel reflection for the different boundaries [11,12], and depend on the optical coefficients μ_s, μ_a, g, and n/n_{ext} (relative index of refraction). Monte Carlo methods have been widely used for several transport problems [13,14] and for numerical

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Nomenclature

$\mu_s^{(i)}$	scattering coefficient of the layer (i)
$\mu'_s{}^{(i)}$	reduced scattering coefficient of the layer (i)
$\mu_t^{(i)}$	transport coefficient of the layer (i)
$\mu'_t{}^{(i)}$	reduced transport coefficient of the layer (i)
$\mu_a^{(i)}$	absorption coefficient of the layer (i)
g	anisotropy coefficient
γ	factor characterizing a phase function
p_{HG}	Henyey-Greenstein phase function
p_{GK}	Gegenbauer phase function
α	shape parameter of p_{GK}
g_{GK}	coefficient related to p_{GK}
p_{Mie}	phase function based on the Mie Theory
p_{MHG}	modified Henyey-Greenstein phase function
p_{MGK}	modified Gegenbauer phase function
α_{Iso}	proportion of symmetric component in the modified phase functions p_{MHG} and p_{MGK}
$p_{\delta E,Iso}$	delta-Eddington phase function
$p_O(\theta_O)$	exponentiated cosine distribution function
$p_b(z)$	distribution of ballistic light source along depth z
$p_{IsoForw}(z)$	distribution of diffuse light source along depth z
ω_0	source radius
r_s	spherical radius
θ	angular deviation
ρ	radial distance
z	axial distance (depth)
θ_O	angle defined only at the surface
(x_c, y_c, z_c)	coordinates related to the half-sphere geometry

simulations of photon propagation in multilayered biological tissues [15–19] or within tissue-like diffusing phantoms [20,21]. The knowledge of laser light transport through the human skin allows to improve therapy applications [17], cosmetic analysis [22], or to reproduce the human face with more accuracy [5]. In this last case, the specular and diffuse light coming from the location of the light source which illuminates the skin surface are studied with respect to different observation angles. The effects of the light source shape [23–25], surface roughness [26], optical-clearing [27] and hair density [28] on the photon dose absorbed in the human skin have been well investigated. However, to our knowledge, the influence of the angular distribution of the light source (ballistic, diffuse or Lambertian) on

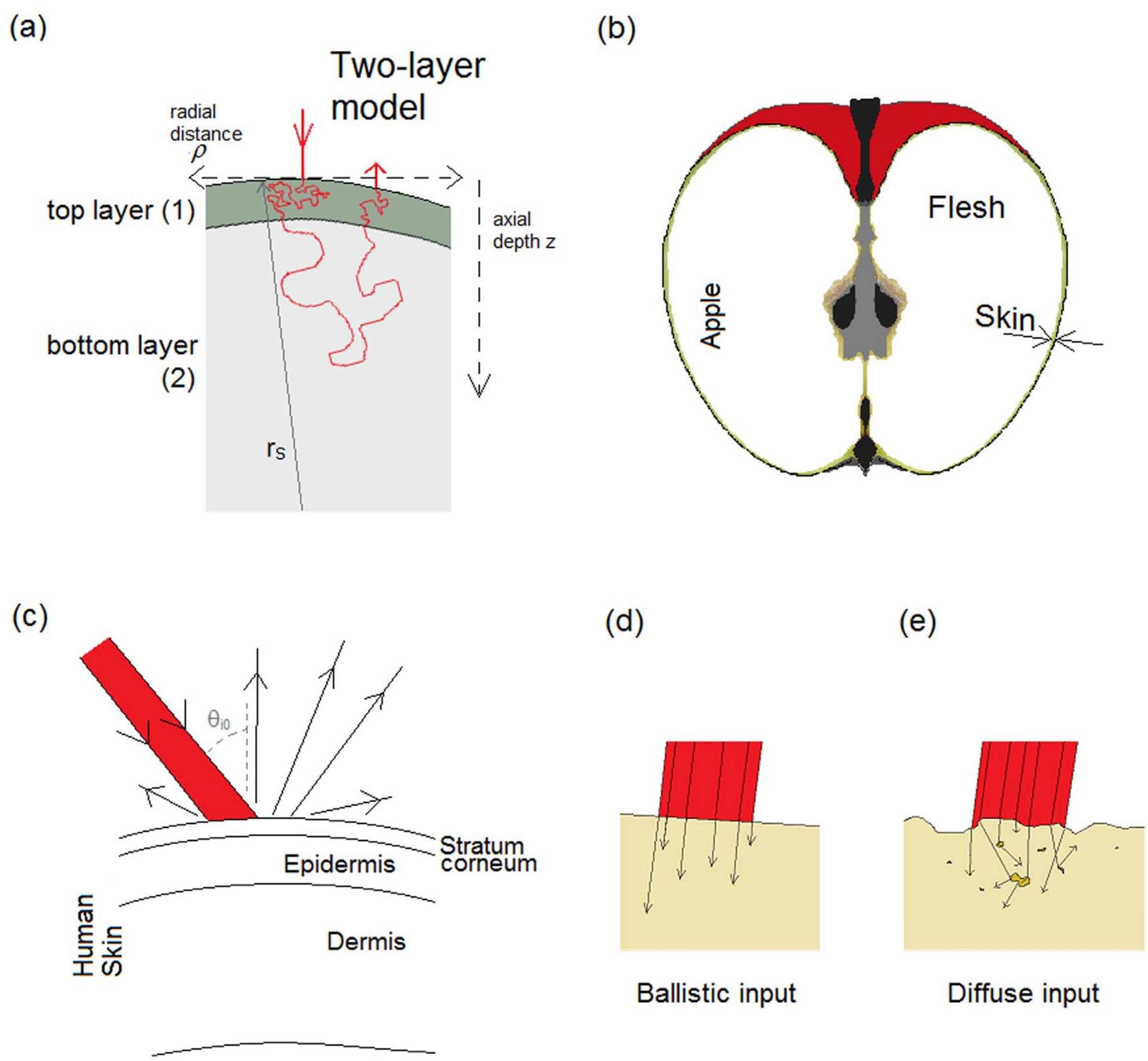

Fig. 1. Schematic pictures of multilayered tissue structures (a) Curved two-layer turbid medium with a top layer (skin), and illuminated by a laser source under normal incidence. (b) Example of top and bottom layers in biological tissues: apple with skin and flesh. (c) Simplified scheme of the human skin illuminated under oblique incident light source. (d) Ballistic and (e) diffusive light sources.