Monte Carlo for Very Thin Layered Media

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Abstract

Many modern applications of lasers involve modeling of radiation energy transport through very thin layers. The interactions of continuous wave and pulsed lasers with skin in dermatological use related to surgery and cosmetic procedures are examples of such. Highly scattering thin layers in skin are best modeled by Monte Carlo method since their interfaces are not perfectly planar and the thicknesses are non-uniform. Due to scattering, interference and other thin film wave effects are not important. Additionally, the common diffusion approximation utilized extensively in modeling bio-medical laser transport is invalid because of the proximity of interfaces where the diffusion approximation is known to be inaccurate.

Traditional Monte Carlo models may, however, inaccurately capture the effect of thin layers. As an example, the very thin epidermis with its highly absorbing melanin is known to influence the laser penetration significantly. If the Monte Carlo model is implemented without special features then the results of the simulation would show no effect of the outer thin layer since the path length of most photons would be significantly larger than the layer thickness and the resulting predicted photon travel would simply not notice the presence of the layer.

In this paper we present the results of using Monte Carlo to accurately model transport of radiation through very thin layers using both the traditional Monte Carlo and that with the new features incorporated. The results have profound implications in the diagnostic and therapeutic applications of laser in biomedicine and surgery.

1 Introduction

Monte Carlo simulations have become increasingly important in developing new diagnostic and therapeutic applications of laser in biomedicine and surgery. Monte Carlo computational models have been used to chart new direction in the development and advancement of new clinical applications, new clinical procedures, resulting in better clinical outcomes. For instance, Monte Carlo based models are being used to develop and optimize treatment procedures, speed wound healing, minimize pain, reduce subjacent tissue damage or injury and predict the extent of tissue damage resulting from a particular thermal treatment method.

Many clinical conditions rely on the ability to deliver energy to biological tissue in order to modify the properties or health of the tissue. Monte Carlo based laser diagnostics [1] and therapeutics [2] applications have become widely accepted as the benchmark for the management and treatment of many clinical conditions. Modern therapies require accurate deposition of thermal energy into biological tissues and laser based therapies have become widely accepted. Photodynamic therapy, selective photothermolysis, laser surgery, tissue welding and cryosurgery are examples of this laser based modern therapies. These therapeutic procedures require accurate modeling of transient deposition and absorption of energy in the regions of interest in the affected tissue. Most previous studies on numerical models that are used to predict energy distribution in illuminated biological tissue layers during laser therapies and diagnostics have been studied extensively. Parabolic diffusion approximation [3] and Monte Carlo simulation models [4] have been considered by many researchers, but models to predict precisely deposition of energy in very thin tissue layers are yet to be fully developed.

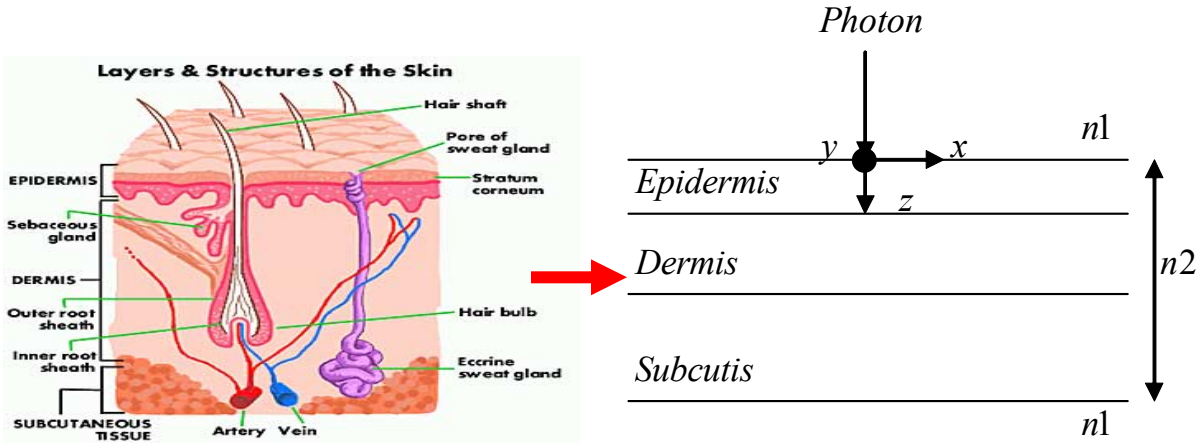
For optically thin tissues like the epidermis and the epithelial layer of the esophagus, numerical models used to predict energy distributions fail partly because of the microscale nature of these layers. Results from traditional Monte Carlo simulations have been shown not to match those obtained from

parabolic diffusion results for tissue samples of thickness less than their mean free path [5]. Experimental investigations of short pulse laser transport through tissue have indicated that although the diffusion approximation seems adequate for very thick tissue samples, it does not match experimental results in other cases [6]. Also when the energy is pulsed, has very short time scale with attendant high heat fluxes, current approaches used in modeling biological thermal phenomena are not proficient at capturing important physical events occurring at or near boundaries or tissue interfaces.

In this paper, laser light scattering for thin layers has been examined for both the traditional Monte Carlo and that with new features added and its effect on the reflection, transmission, and absorption presented.

2 Method

Monte Carlo simulation technique is a common statistical method used to model light propagation in tissue and is based on the concept that photons can be scattered, absorbed or exit the model under investigation Fig. 1 [7].



(a) (b)

Figure 1: (a) Typical skin sample [7], (b) Multi layer skin model used in the simulation.

The simulation process is initiated by launching light beam which is considered to be split into many photon packets, each with initial weight, W, into the biological medium in a given direction. After a distance, L, the photon packet is assumed to interact with the medium, and a fraction, ΔW of this packet is deposited at the point of interaction after which a new direction for the photon packet is simulated. A repetition of this process continues until the photon packet is absorbed or exits the medium. Termination roulette is used to avoid simulating small weights. The path length between two successive interactions or scattering event L, the deflection angle after the interaction in the polar and azimuthal directions θ & φ, respectively, and the deposited fraction at j^{th} interaction are determined by the following equations [8]:

$$L = -\frac{\ln(R1)}{\mu_a + \mu_s} \tag{1}$$

$$\theta = f^{-1}(R2) \tag{2}$$

$$\varphi = 2\pi(R3) \tag{3}$$

$$\Delta W(j) = W(j-1)\frac{\mu_a}{\mu_a + \mu_s} \tag{4}$$

$$f(\theta) = \frac{\int_0^{\theta} p(\varphi)\sin(\varphi)d\varphi}{\int_0^{\pi} p(\varphi)\sin(\varphi)d\varphi} \tag{5}$$

For time resolved analysis, the total optical path length of each photon bundle inside the medium is converted to time of flight, t, of photon by using the speed of light of the medium c thus:

$$t = \frac{L_{total}}{c} \tag{6}$$

3 Results and Discussion

The distribution of photon energy absorbed in each layer is shown in Fig. 2, while reflection and transmittance from the layered media is shown in Fig. 3. The top surface of the epidermal layer is considered as a black or a reflecting boundary. Black boundary, for the purpose of this work implies that a photon packet once inside the tissue cannot be reflected out to the surrounding media. This is equivalent to insulation boundary condition. For reflecting boundary the photon after multiple scattering and not being absorbed in the tissue escapes from the tissue surface. The traditional Monte Carlo profile has a continuous photon absorption distribution. The exact transition from layer to layer is not dramatic as there is no clear dividing line between layers, despite the large difference in layers absorption contrast.

For the Monte Carlo with special features shown in Fig. 2 as 'New' and 'Traditional', the absorption profile in the layered skin media has a sharp discontinuity at each layer to layer interface. Photon interaction with the turbid skin model is captured explicitly at each level and on each layer, and gives a vivid picture of events occurring during each step of the simulation. In the traditional method, there is no clear delineation of photon absorption between respective layers.

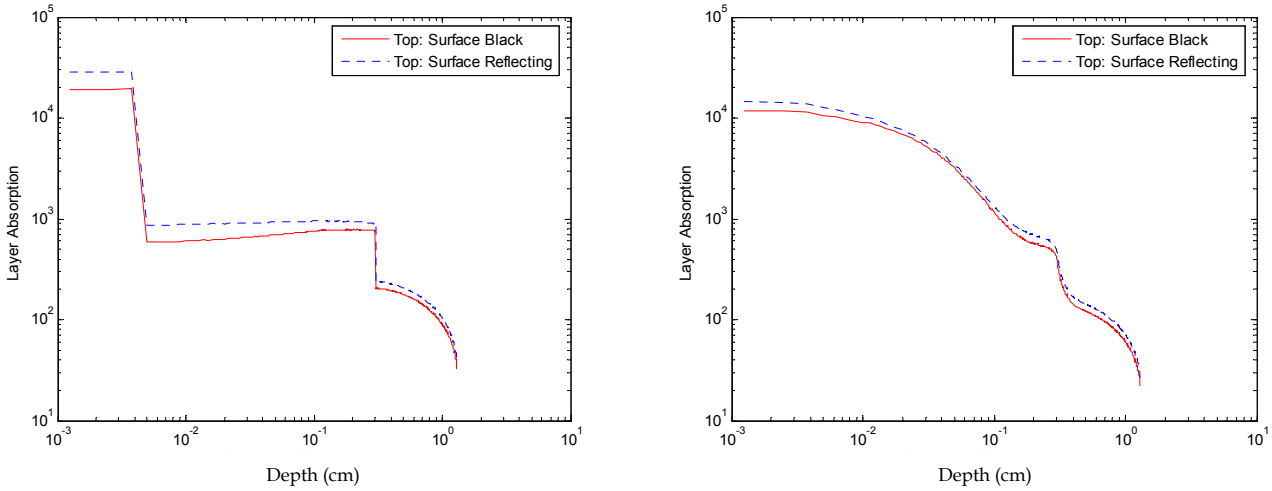
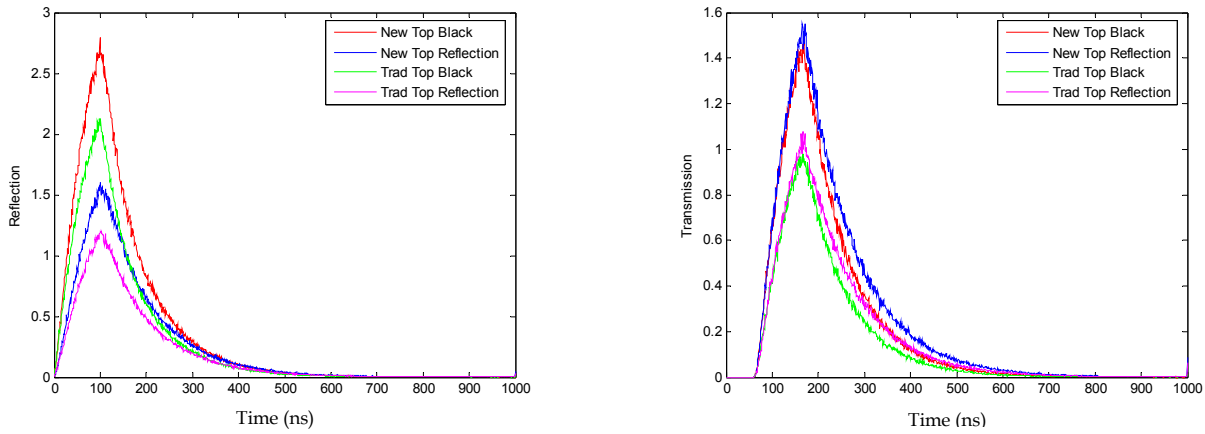


Figure 2: (a) Monte Carlo with new features added (b) Traditional Monte Carlo: Energy deposition in epidermis (L1), dermis (L2) and subcutaneous (L3) layers for both reflecting and non-reflecting epidermal layer with L1 = 0.005 cm, L2 = 0.30 cm, L3 = 0.99 cm, μ_a = 8.8, 0.26 and 0.07 cm^{-1} for epidermis, dermis and subcutis, μ_a = 20 cm^{-1} for all layers, and n1 = 1.0, and n2 = 1.37.

The reflection and transmission intensity for Monte Carlo with new features added and the traditional Monte Carlo for situation where the epidermal layer is black and reflecting is shown in Fig. 3. This enhancement was made possible by using the optical distance of each layer as intermediate start and end boundary condition and hence photon path length traveled after an interaction event is captured in the layered where the event occurred. The result presented above may provide a route to more realistic

determination of energy deposition in very thin layered media, noting however that these results are also dependent upon chosen optical properties, age, race and physiological factors of each individual.



(a) (b)

Figure 3: (a) Reflection intensity and (b) Transmission intensity: For epidermis (L1), dermis (L2) and subcutaneous (L3) layers for both reflecting and non-reflecting epidermal layer with L1 = 0.005 cm, L2 = 0.30 cm, L3 = 0.99 cm, μ_a = 8.8, 0.26 and 0.07 cm^{-1} for epidermis, dermis and subcutis, respectively, μ_a = 20 cm^{-1} for all layers, and n1 = 1.0, and n2 = 1.37.

4 Conclusion

In this paper, we have presented a novel Monte Carlo simulation with features that calculates photon propagation and energy deposition, reflection and transmission in multi layered skin explicitly for each layer. This result will improve our understanding of light tissue interaction and its effect on dermatological applications relating to surgery and skin rejuvenation.

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References

[1] Thueler, P. Charvet, I. Bevilacqua, F. Ghislain, M. Ory, G. Marquet, P., Meda, P. Vermuelen, B. & Depeursinge, C. "In Vivo Endoscopic Tissue Diagnostics Based on Spectroscopic Absorption, Scattering, & Phase Function Properties", J. of Biomedical Opt., **8**, 495-503 (2003).

[2] Anderson R R. and Parish, J. A. "Selective Photothermolysis: Precise Microsurgery by Selective Absorption of Pulsed Radiation", Science, **220**, 524-527 (1983).

[3] Gemert, M. J. C. Jacques, S. L., Sterenborg, H. J. C. M. and Star, W. M. "Skin Optics", IEEE Trans. Biomed. Eng., **36**, 1146-1154 (1989).

[4] Wilson, B C. "A Monte Carlo Model for the Absorption and Flux Distributions of Light in Tissue", Med. Phys., **10,** 824-830 (1983).

[5] Gandbakche, A. H. Nossal, R. and Bonner, R. F. "Scaling Relationships for Theories of Anisotropic Random Walks Applied to Tissue Optics", Applied Optics, **32**, 504-516 (1993).

[6] Yodh, A. and Chance, B. "Spectroscopy and Imaging with Diffusing Light", Physics Today, **48,** 34-40 (1995).

[7] Healthy-Skin-Guide, http://www.healthy-skin-guide.com/skin-diagram.html

[8] Yamada, Y., 1995, "Light-tissue Interaction and Optical Imaging in Biomedicine, Annual Review of Heat Transfer, **6**, 1-59 (1995).