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Low Level Laser on Multilayer Skin Tumour using Monte - Carlo Simulation

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Abstract

The powerful narrow beam of single wavelength light that laser produces was the first "solution looking for the problem in 1960". Theodore Maiman created it 1960 by illuminating a high-power flash light on a ruby rod on a silver coated surface at California's Hughes Research Laboratory. From the most cutting-edge quantum physics labs to hospital. Laser is now ubiquitous in modern science and technology. When a laser heats up its target, a phenomenon known as photothermal interaction occurs. Proteins are denaturized, mitochondrial membrane permeability is enhanced and the mitochondria eventually evaporate. In this paper Monte-Carlo simulation method is used for the Laser tissue interaction.

This study aims to understand the temperature distribution in a multi-layered skin model during laser-induced thermotherapy for cancer treatment. model includes the epidermis, dermis, subcutaneous fat, muscle, blood, and an embedded tumour. The study systematically investigates the effects of various parameters such as wavelength, laser intensity, tumour absorption coefficient, and irradiation time. Proposed model can explore both the individual and combined effects of the parameters on the temperature distribution in the skin model by methodically varying the parameters. The findings may help to improve laser-induced thermotherapy, which may result in more precise and efficient skin treatment.

Keywords: Laser; Tissue; Monte-Carlo simulation

Introduction

The low-level laser therapy (LLLT) is getting more consideration and applying widely in the medical arena. This application promotes tissue regeneration, reduces inflammation, and relieves pain. Unlike other medical laser applications, LLLT does not have an ablative or thermal mechanism, but rather a photochemical effect which means the light is absorbed and causes the photochemical reactions inside the biological tissue. The reason why the technique is termed low level is that the optimum levels of energy density delivered are low and it is not comparable to other forms of laser therapy as practiced for ablation, cutting, and thermal tissue coagulation. The degree of photochemical reactions and the biological responses depends on the absorbed dose of light in biological tissue. The depth of laser light penetration in the tissue depends upon its optical properties which vary according to the wavelength variations [1]. To get a good treatment, the physician must choose the laser and laser parameters such as Laser beam power, Laser spot size and duration of the treatment time.

For modelling any type of laser treatment (photochemical, thermal, or ablative), it is important to evaluate the distribution of photons in tissue. In thermal and ablation, light distribution or proportional to the heat source. An exact assessment of laser propagation in the tissue requires a model that characterizes the spatial distribution of photons in tissue structure, their absorbing properties, and

refractive indices. This is effectively done by Monte Carlo simulation. Monte Carlo results are consistent with transport theory, which is an analytical theory for describing light propagation in turbid media. The power of the Monte Carlo methods lies in its ability to handle virtually any source, detector, and tissue boundary conditions, as well as any combination of tissue optical properties [2]. the Monte Carlo method acknowledges an issue for any simulation technique, the probability of varying outcomes cannot be firmly pin pointed because of random variable interference. therefore, a Monte Carlo simulation focuses on constantly repeating random samples. a Monte Carlo simulation takes the variable that has uncertainty and assigns it a random value [3]. The model is then run and a result is provided. this process is repeated and again while assigning many different values to the variable in question. Once the simulation is complete, the results are averaged to arrive at an estimate. Monte Carlo methods are versatile and can model a wide variety of tissue geometries [4]. It is particularly useful in the field of tissue optics for modelling how light interacts with complex tissues. Monte Carlo Simulation can provide detailed information about all the aspects of the interaction of light with tissues, including reflection, transmission, and activation.

When the Laser light interacts with the tissues then the photon may be absorbed or unabsorbed within the tissue. Light is assumed as a stream of photon where the interaction of light depends on the properties of incident light and optical properties of the tissues. absorption and scattering in the tissue, reflection and transmission at the boundaries decide the number of photons which gets inside the tissue [5]. Every photon undergoes frequent scattering. Photon can be absorbed by the tissue chromophore, except for scattering. Photon propagation in tissue is modelled, which characterizes the spatial distribution.

In this work, the goal is to develop and validate a simulation model for the laser and tissue interaction using Monte Carlo Method. In this paper Literature review is conducted in section 2 followed by Introduction in section 1, section 3 explains the study and experiment that shows us laser tissue interaction model for low level laser therapy.

Literature Review

Monte Carlo simulations have become an indispensable tool in the field of biology, enabling researchers to study complex biological systems, model the behaviour of biomolecules, and predict various biological processes. Continued advances in computational techniques and increasing computing power continue to expand the role of Monte Carlo simulations in biological research. The first use of the Monte Carlo method for photon transport in biological materials was Adams and Wilson (1983), which considered isotropic scattering [6]. Keijzer et al. (1987) introduced anisotropic scattering into the Monte Carlo simulation of biological tissues, implementing a simulation that propagated photons using cylindrical coordinates, which introduced the Hop/Drop/Spin nomenclature for organizing the program [7]. Prahl et al. (1989) reformulated the program using photon propagation based on Cartesian coordinates, which made the program much simpler to convey in written form [8]. Wang and Jacques (1993) adapted and augmented the work of Keizer and Prahl to write the program Monte Carlo Multi-Layered (MCML) that considers tissues with many planar layers with different optical properties [9].

Yu shimojo et al. (2023). proposes a simulation making use of Monte Carlo, that is demonstrated with the aid of undertaking optical residences measurements and laser irradiation experiments is performed on porcine liver tissue. In evaluation, study found that simulations passed static optical belongings-based techniques by means of more than 2.5 instances in accuracy when calculating coagulation and vaporization regions, specially at excessive-electricity irradiation settings [10].

Zoya Alam and Raju Poddar (2023). Proposes The energy deposition and temperature distribution estimation obtained by the Monte Carlo simulation method. A real-time measurement of the temperature profile was also performed. The experimental results were in close congruence with the simulation result. The simulation results show good reproducibility of the real temperature distribution. Monte Carlo method can, thereby, be used in estimation and optimization laser induced processes [11].

Pham Thi Tien, T. A. Tiu, and Trung Nghia Tran (2022). Proposes a Monte Carlo method to simulate the propagation of low-level laser light at wavelengths (633 nm, 780 nm, 850 nm, 940 nm) from the human back skin surface through the skin tissues to the lung. As a result, each treatment's appropriate wavelengths, dose, and energy is selected [12].

Trinh Tran Hong Duyen (2020). describes the simulation results of low-level laser propagation from skin surface at the lower spine, the knee, the femur and the prostate gland with four wavelengths (633 nm, 780 nm, 850 nm, and 940 nm) using Monte Carlo method. results shows that study is used to develop a low-level laser therapy device, that could be used in clinical for treating the fracture, knee osteoarthritis, spinal degeneration, and benign prostatic hypertrophy [13].

Haicheng Li, Changxing Zhang, and Xue Feng (2019). proposed this work, for optimizing the design of the skin-like optical device using Monte Carlo method to investigate the light distribution after scattered and absorbed by a human tissue. Different parameters of light source and blood vessels are used to simulate the device and human tissue deformation respectively. simulation results shows that the deformation of the device and human tissue can produce non-linear effects on the characteristics of the exited lights. Device has been developed for the skin-like device using the simulation [14].

Ting Li et. al. (2018). proposed a precise voxelized three-dimensional Monte Carlo method (MCVM) to simulate photon propagation within Visible Chinese human (VCH) head at different level of stroke with varied parameters of beams. found that Gaussian beam with larger or the same size of haemorrhagic region generates the highest and relative homogeneous therapeutic outcomes, while the Top-hat beam performed better when haemorrhagic region is much bigger than beam size. results demonstrate the great potential of using VCH and MCVM in optimizing LLLT treatment parameters for stroke and in guiding future instrumentation of LLLT on haemorrhagic stroke [15].

Nasouri B, Murphy TE, Berberoglu H. We present a three-dimensional, multilayer reduced-variance Monte Carlo simulation tool for studying light penetration and absorption in human skin. Local profiles of light penetration and volumetric absorption were calculated for uniform as well as Gaussian profile beams with different spreads over the spectral range from 1000 to 1900 nm. The results showed that lasers within this wavelength range could be used to deliver energy effectively and safely to specific skin layers as well as achieve large penetration depths for treating deep tissues, without causing skin damage. In addition, by changing the beam profile from uniform to Gaussian, the local volumetric dosage could increase as much as three times for otherwise similar lasers. We expect that this tool along with the results presented will aid researchers in selecting wavelength and laser power in LLLT [16].

Parvin et. Al. (2009). Conducted a simulation study using Monte Carlo simulation and performed during LLLT with laser power density smaller than 500 mW/cm^2 to determine the spatial photon density as well as the corresponding temperatures contours. Based on this simulation, He has shown that the backscattered photons in dermis layers due to multiple scattering significantly contribute to change in the photon density along propagation axis and in radial direction, comparing with Lambert-Beer and Welch correlations [17].

Methodology

Monte-Carlo Simulation and Heat Transfer Model

When the laser light irradiates on the skin tissue, light is absorbed near the laser irradiation area and scattered by the medium. To analyse these behaviours, the Monte Carlo method is used in the field of biological energy transfer. This process involves the outcome of the behaviour of photons illuminated by randomly selected photons, considering not only photons absorbed by the medium, but also photons scattered simultaneously [18]. Figure shows the photon Launching flow diagram where The box “Launch photon” initializes the photon packet position, direction.

In this study we are developing a five-layer skin tissue model with specific interfaces, and different optical properties. For the implementation, considering Five skin layers: Epidermis, Papillary Dermis, Reticular Dermis, subcutaneous fat, Blood [19, 20]. Specify the interfaces between these layers, as mentioned in the figure 2. For each layer, define the optical properties, including the absorption coefficient (μ_a) that defined as a probability per infinitesimal unit of optical length, scattering coefficient (μ_s) as the photon scattering probability per infinitesimal unit of optical path length, the anisotropy factor (g) is the average value of the cosine of the deviation angle, and thickness of each layer.

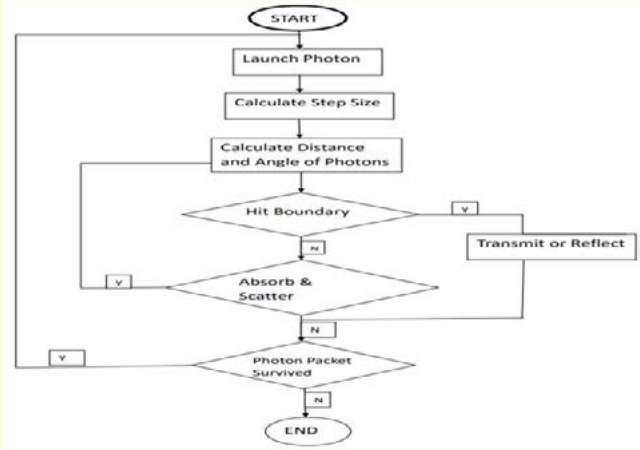

Figure 1: Monte-Carlo Simulation Flow diagram for photon generation.

Parameters	***Epidermis***	***Papillary Dermis***	***Reticular Dermis***	***Subcutaneous Fat***	***Tumor***	***Blood***
Thickness [mm]	0.08	0.5	0.6	7.82	0.1-1.0	2
Density **ρ** [Kg/m^3]	1200	1200	1200	1000	1030	1060
Specific heat capacity C_p $/Kg.K$	3589	3300	3300	2500	3852	3617
K [$^W/_{m.K}$]	0.235	0.445	0.445	0.19	0.558	0.187
Absorption Coefficient (μ_a)	0.4	0.38	0.48	0.43	0.08	6.79
Scattering Coefficient (μ_s)	45	30	25	5	1.28	458.58
Anisotropy factor (g)	0.8	0.9	0.8	0.75	0.925	0.99

Table 1: Thermal and optical properties of normal tissue and cancer tissue parameters in SI units [19, 20].

Materials and Methods

Develop a skin model

The skin covers the whole body and provides protection to internal organs from environment. The skin is a turbid medium, where the blood and pigment content are distributed heterogeneously. Figure shows the anatomy of the skin. The skin has three main layers that are:

(i) Epidermis: is the top layer of the skin, and comprised of millions of dead skin cells. Epidermis has a thickness of 100 μm, contains melanin pigment, and does not have any blood vessels [18].

(ii) Dermis: is the underlying connective tissue, which is composed of nerves, blood vessels, sweat glands, and hair follicles [33]. The thickness of the dermis ranges from 1- 4 mm [18].

(iii) Hypodermis: is located under dermis and contains subcutaneous adipose tissue. The thickness of hypodermis ranges from 1 to 6 mm [18].

In this proposed methodology simulation of Laser tissue done on tumour cell and thermal analysis is achieved using opensource Matlab library MCmatlab considering all the related tumor parameters in the human skin, for that a 100 × 100 × 100 voxel model of a cylindrical blood vessel of radius 0.1 cm embedded with deep in dermis and layer of epidermis on the surface. Figure 1 shows the geometry, visualized using the interactive 3-D volumetric slice plotting used for many different plots in MCmatlab. Table 1. shows the parameters used for all the skin properties. Skin model is a cube of 0.1 cm^3 considering all cuboid boundary are escaping.

For the Laser beam parameters as shown in table 2. 810nm wavelength and 100 mW of power Laser is used for the determination of optical properties in the excitation of light. The beam of incident light is 0.03 cm. Gaussian with radial near field distribution. Beam is focused on [x, y, z, ϑ] as [0, 0, 0, 0] radian. Model is analysed for insulating boundaries with on time and off time of the pulse as 2 ms. And 3 ms and 0.01 second as a relaxation time. Initial temperature of the tissue is to taken as 37^0C and expected range is shown on the plot 37-100^0C.

The blood vessel sample is having radius 0.01 and thickness 0.04 cm., epidermis, dermis thickness is 0.02 and 0.03 cm respectively in the geometry model.

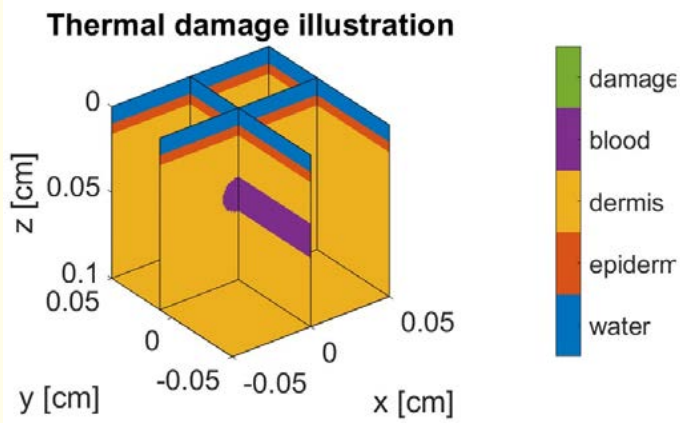

Figure 2: Thermal damage analysis using Monte Carlo on skin geometry.

Parameters of Laser Baem

The propagation of collimated laser beam with normal to the surface which has uniform irradiation attenuated into the tissue can be defined by absorption coefficient μ_a and scattering coefficient μ_s represented as fluence rate along the z direction:

$$F(z) = F_o\,(1 - r_{sc})e^{-(\mu_a+\mu_s)z}$$

Penetration depth for the collimated beam is $\delta = 1/\mu_t$, where percentage of collimated beam can be reduced by 37% of its initial value. Laser diameter is set to be 5mm. Fluence rate is directly proportional to power (W) and it is a function of distance from incident light Laser source in to the tissue skin model as shown in figure 3. For the Laser parameters as shown in table 2.

Results

In the simulation results the Monte-Carlo method is used in Low level laser therapy for the analysis of thermal model of laser tissue interaction as shown in figure 4 a. and in figure 4 b.

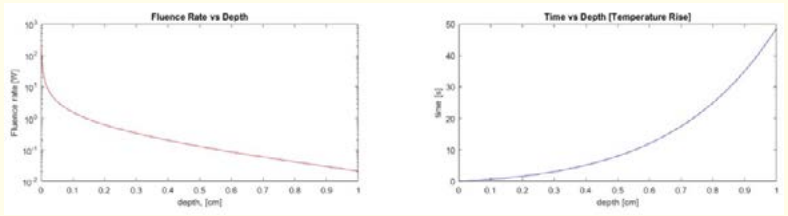

Figure 3: Fluence rate Vs Depth and Time Vs Depth.

S. No.	Parameters Name	Value
(i)	Laser Power	100 mW
(ii)	Energy reflectivity coefficient	0.024
(iii)	Laser spot size	2 mm
(iv)	Laser Wavelength	808 nm.

Table 2: Laser Beam Parameters.

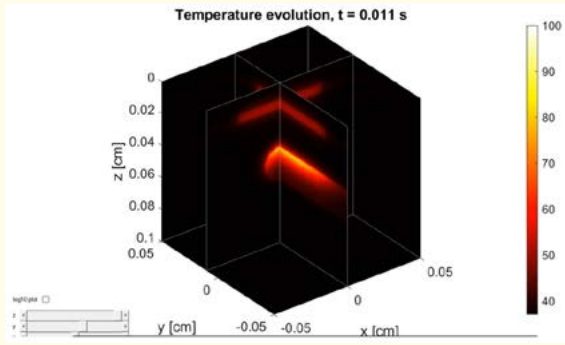

Figure 4 a: Temperature evaluation on skin model using Monte-Carlo simulation at t= 0.011s.

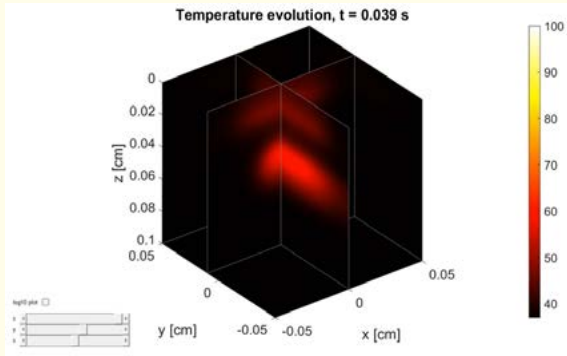

Figure 4 b: Temperature evaluation on tissue skin model using Monte-Carlo simulation at t=0.039s.

Conclusion

For the implementation of Monte Carlo simulation in the Laser tissue interaction with tumor skin tissue open source MCML (Monte Carlo Modelling of Light Transport Multi-layered Tissues) is used which is very important tool in the field of biomedical optics and is commonly used for modelling of light with tissues.

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