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Modeling of laser tissue interaction by the Monte Carlo Method

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ABSTRACT

The study of the physical process of a pulsed laser interacting with human brain tissue is important to identify the energy transport of photons in a strongly diffused zone. The purpose of this article is to describe by a numerical simulation method (Monte Carlo), the light bundle formed by the source-detector pair by scanning a portion of the volume of diseased tissues. In the present simulation, we use the experimental results: the absorption and scattering coefficients respectively μ_a and μ_s. We follow the paths of a random walker and we plot for each event as a first step, the relative fluence rate, the reflectance and the transmittance of the signal in terms of respectively depths of penetration and the times expressed in *(ps)* using a cylindrical geometry. The second step is to study the distribution of the photons of the recorded at different positions, dependent primarily on the ultra-short pulsed laser source in femtosecond wavelength of 800nm. We consider the spherical coordinates (R,θ,φ) and time t. Thereafter, we compare these results with those calculated with the Cartesian coordinates (x,y,z).

Introduction

In this study, we observed first the photon migration with multiple scattering events in cylindrical geometry model of human brain, then, we followed the luminous packet in the three-dimensional head model of a human based on Monte Carlo simulations. 10^5 photons were emitted into this model using femtosecond lasers pulsation. The received photons of the detectors were traced. In this paper, the new contribution is set as follows:

1. In previous studies, the results of Monte-Carlo simulations were usually based on a semi infinity cylindrical geometry [1],[3]. In our case, we simulate the migration of photons in a human brain on the basis of realistic three-dimensional adult head model obtained by means of a mathematic model based on modified algorithm [2].

In Section 2, we develop this mathematical geometry, while describing the basic principle of Monte Carlo. In section 3, we introduce the Monte Carlo algorithm modified for this model structure of a human brain in three dimensions in terms of Cartesian coordinates and spherical coordinates. Finally, Simulation results are discussed in Section 4.

Formulation of the problem

We consider a short pulsed infrared laser *IR 800nm*, penetrating the sample of *3D* geometry (Fig. 1). The photons are launched from an isotropic point source of unit power $P = 1mW$ inside a homogeneous media [2].

The information about medical diagnosis is defined by mathematical models. In the following study, we consider a packet of photons of light energy penetrating the volume of a human brain. We use a semi-spherical volume with a section of $\pi \times r^2$ and a radius equal to R. The specific intensity defined by the flow of energy at a given time t is represented by its radial position $\vec{r}$ (distance from the source to a position determined in the tissue) and its direction of propagation $\vec{s}$. We introduce the photons from the laser source at the red point with the initial spherical coordinates (r_0,θ_0,φ_0). Indeed, we recall that we are in the 3D space of the human brain and we introduce an anatomical reference mark; the green point of coordinates $(0,0,0)$ which allow us to define accurately the other points. Finally, we recover the remaining photons through the black point for dealing with information obtained see Figure 1.

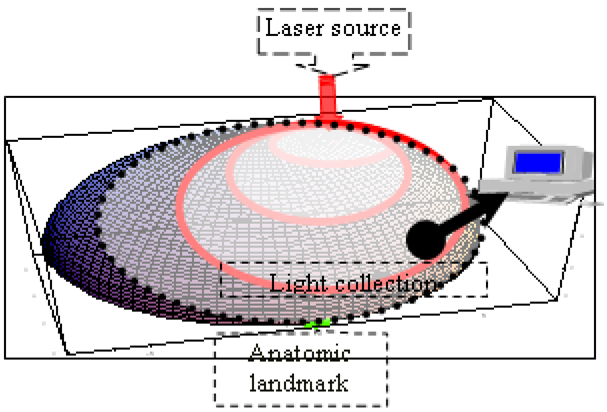

Figure 1. Distribution of laser light in a spherical tissue [4]

In this volume, part of the energy is absorbed while the other is diffused. Outgoing light intensity of this volume following this same direction is detected and is analyzed.

The variation of the luminous flux $I(\vec{r}, \vec{s}, t)$ expresses itself by [6]:

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$$\frac{dI(\vec{r},\vec{s},t)}{dl}=\frac{1}{c}\frac{\partial I(\vec{r},\vec{s},t)}{\partial t}+\vec{s}.\vec{\nabla}I=-\mu_t.I(\vec{r},\vec{s},t)$$
$$+\frac{\mu_t}{4\pi}\int_{4\pi}p(\vec{s},\vec{s}\,').I(\vec{r},\vec{s}\,',t).d\Omega' + \varepsilon(\vec{r},\vec{s},t) \quad (1)$$

Several mathematical models have been used from this integral-differential equation to describe the propagation of light in a turbid media.

The most simple equation is called diffusion equation; it is expressed by [7]:

$$\frac{1}{c}\frac{\partial \varphi}{\partial t}-D\,\Delta\varphi+\mu_a\,\varphi=S \quad (2)$$

When the photon tries to leave the media, the probability of an internal reflection is calculated using the Fresnel equation [2]:

$$R(\theta_i)=0.5\times\left[\frac{sin^2(\theta_i-\theta_t)}{sin^2(\theta_i+\theta_t)}+\frac{tan^2(\theta_i-\theta_t)}{tan^2(\theta_i+\theta_t)}\right] \quad (3)$$

$\theta_i = cos^{-1}\,\mu_z$: is the incidence angle at the limit of biological tissue.

θ_t : is the transmission angle which is expressed by the law of Snell:

$$n_i\,sin\theta_i = n_t\,sin\theta_t \quad (4)$$

If a reflection occurs, then the photon is retro diffused in the media with a suitable distance and the flight of this photon continues. Otherwise, the photon is stopped and a new photon is launched in the medium at the same preset place of the source.

Results and Analysis

The principle of this numerical resolution is to simulate the flight of a large number of photons in a turbid human brain. The source fixes the initial spherical coordinates (r_0,θ_0,φ_0) in an orthogonal Cartesian reference mark, the cosine directors (u_0,v_0,w_0) as well as the starting time of the photons t_0. These parameters are defined according to the characteristics of the real source of light. We call photons a luminous energy defined by a spatial position and a direction of propagation. These photons are not true photons. To the beginning of simulation, we affect for each photon a statistical weight equal to one.

For each interaction, the weight of the photon is multiplied by the probability of no absorption; the albedo $\omega_0 = \mu_s/\mu_t$, between two events, the light is propagated without any interaction. The fraction of the statistical weight remaining after several interactions corresponds thus to the probability for which the history of the photon occurs.

We consider a homogeneous biological media: to work with the spherical coordinates.

- The distance of the light propagation is between *0.5cm* and *3cm*.

The diagram is simple; it uses a laser with short impulses of femtosecond type and which emits in the near infrared *NIR* at *800nm* wavelength. It follows a precise optical path until it reaches its target. Then the photons are evacuated via the optical fiber at the specter sensor and at the **PC** in order to do a treatment (see Figure 2).

In our spherical model, we send 10^5 photons with optical parameters (grey matter) [10] $\mu_a = 0.1\ cm^{-1}$, $\mu_s = 100\ cm^{-1}$, $g = 0.9$ and $n = 1.4$ with a radial depth $R = 0.75\ cm$ and irradiation of *1 mW* for a pulsed time of *20 ps* by *binT* (total time = *2 ns*) and for binarizations in spherical coordinates r, θ and φ respectively of *0.075 cm* by *binr*, *PI/40* by *bin*θ and *PI/20* by *bin*φ. In this paper, we represent the modified algorithm simulated by the Monte Carlo method with using the C++ language which describes the flight of photons in spherical coordinates.

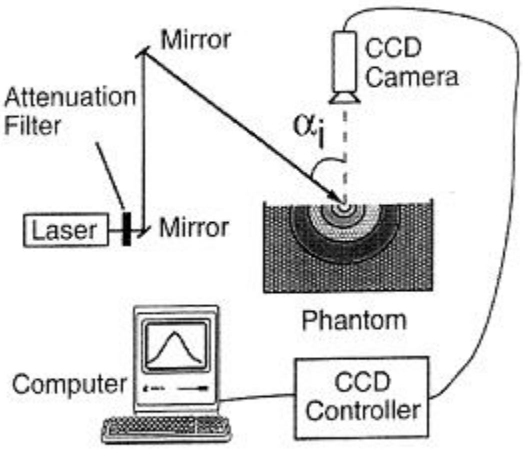

Figure 2. Experimental device

We regroup the results calculated by the modified code of Monte carlo at a semi spherical circular surface [5]. We draw *Photons_r*θ according to *(Pos_r – Pos_*θ*)*, (see Figure 3). We note the existence of a photonic density in the center of the circular medium (close to the positions *Pos_r = 0 cm*) but decreases progressively when we move to the center at the positions *Pos_r = 0.42 cm*, by scanning the entire surface as a function of the azimuth angle between -π and π. We can also see an increase of the photonic density at the edges of the tissue of the positions *Pos_r = 0.75 cm* [6].

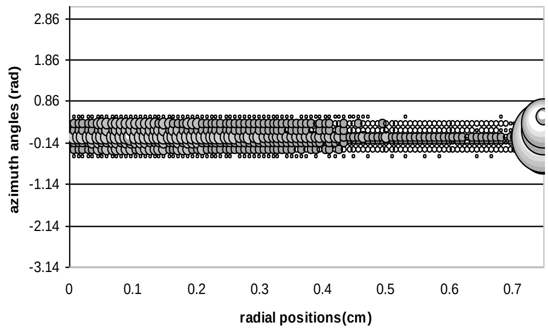

Figure 3. Representation of the photons on a semi-spherical surface according to (r,θ)

Comparing these results with those calculated according to the Cartesian coordinates; the representation in the plane in x and y (see Fig.4), we find a good relationship with the results found in literature [9].

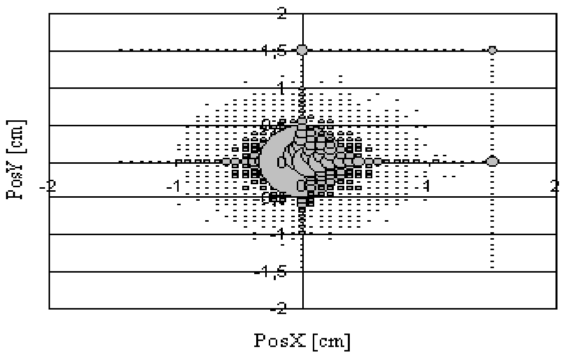

Fig 4. Planar representation of the photons on the planar surface according to (x,y)

All these results are validated by the Boltzmann distribution function in linear regime [8]. We also draw the curves of Figure 5 and Figure 6, giving the reflection and transmission signals as a function of time *T(ps)*, following the same initial conditions. We can affirm a good relationship between these all results. We also note that these graphs present disturbances due to noise in the calculations [10].

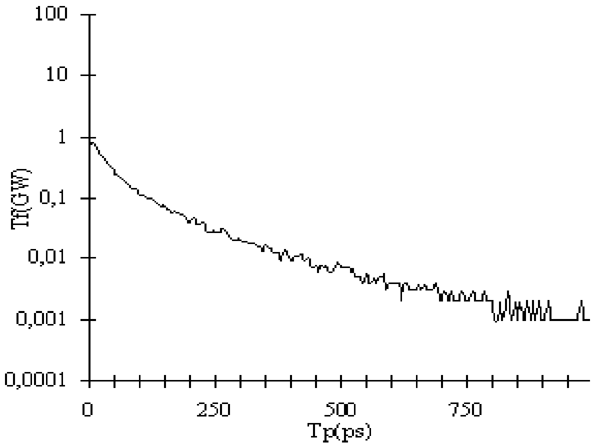

Fig 5. Representation in logarithmic scale of the transmittance according to T_p

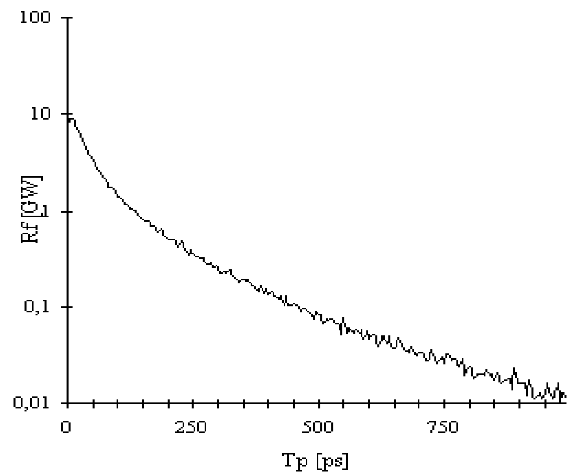

Fig 6. Representation in logarithmic scale of the reflectance according to T_p

Conclusion

In this paper, we have used a numerical method of Monte Carlo to resolve the propagation of photons in this complex structure, the use of the pulsed femtosecond laser beam for the diagnosis informs us on the cerebral tissues state and give us important information that are detected and analyzed.

It is necessary to know that the study to this spherical model is not simple, that's why we have proposed a semi spherical model, supposing on one hand, the volume of the propagation of photons spherical (r,θ,φ), and on the other hand, we have used the two conditions of thresholds: $(x^2+y^2+z^2) \geq R^2$ and $z \leq 0$, what permitted us to calculate the number of photons backscattered from this surface.

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