Pulsed Light Reflection for the Simulation of a Spherical Biological Tissue by Using Monte Carlo Method

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Abstract

The study of the physical process of a pulsed laser interacting with spherical biological tissue is important to identify the energy transport of photons in a strongly diffused cerebral zone of a human brain. The purpose of this article is to describe by a numerical simulation method (Monte Carlo) the light bundle formed by the source-detector pair into the brain to simulate the effect of variation of the optic absorption of a cerebral zone at the time of a physiological event. In the simulation, we use the experimental results that the absorption and scattering coefficients respectively μ_a *and* μ_s. *We follow the path of a random walker and we plot for each event as a first step, the distribution of the photons that we record, at different positions depending on the spatial spherical coordinates* (R,θ,φ) *and time positions t. Thereafter, we compare this results with those calculated with the cartesian coordinates (x,y,z), and thus according to the random distribution of the photon number, we can diagnose and affirm the state of the cancerous tissue from healthy tissue.*

Keywords: *Pulsed laser, cerebral zone, Monte Carlo simulation, spherical coordinates, cartesian coordinates*

1. Introduction

There exists considerable current interest in the use of optical methods for medical imaging, diagnosis and therapy [1]. This is motivated by the growing maturity of lasers, fiber optics and associated technologies because of which practical realization of the considerable potential of the optical approaches has now become feasible. Encouraging results have already been obtained for use of optical techniques for in situ monitoring of tissue parameters, discrimination of diseased tissue from normal, mammography, and several therapeutic applications. For most of these applications, in particular for the use of light in diagnostic, it is important to be able to predict the spatial distribution of light in the target tissue. This is rather involved because the biological tissue is inhomogeneous and the presence of microscopic inhomogenities (macromolecules, cell organelles, organized cell structure, interstitial layers etc…) makes it turbid. Multiple scattering within a turbid medium leads to spreading of a light beam and loss of directionality. A rigorous electromagnetic theory based approach for analyzing light propagation in tissue will need to identify and incorporate the spatial/temporal distribution and the size distribution of tissue structures and their absorption and scattering properties. Several significant advantages of NIRS brain imaging include high biochemical specificity, compact system setup, and relatively low cost. Near-infrared light in the wavelength range from 650 to 950 nm can penetrate the adult skull and propagate while in the brain [2]. With brain activation, the oxyhemoglobin pours into a specific region that corresponds to neuron activation. The different oxygenation indicates the changes in brain function with neurovascular coupling processes. Based on the modified Beer-Lambert's Law (MBL), the brain activation of a specific region can be measured from the detected light signals. As mentioned above, the information regarding the brain was associated with detected optical signals that strongly depend on the separation distance between the source and the detector. In this study, we observed the photon migration with multiple scattering events in a three-dimensional head model of a human based on Monte Carlo simulations. 10^5 photons were emitted into the head 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 [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 [4].
In several biomedical applications, changes in the absorption coefficients µa are determined in vivo by several wavelengths. Our interest is in the description of the distribution of the photons, the application of diagnostic by using the near-infrared laser IR. In this application, the sample is illuminated by a point source or a pencil beam. The optical properties of tissue are obtained from the intensity reemitted by the geometrical structure as a function of distance from the origin point [5]. The paper is organized as follows: 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.

2. Mathematical Models

A. Governing Equations

We consider a short pulsed infrared laser *IR 800nm*, penetrating the sample of *3D* geometry (Fig. 1). The information about medical diagnosis are defined by mathematical models. Therefore, we introduce the following assumptions:

1. All media of the human brain possess homogeneous optical properties.
2. The tissue is structured; the thickness of the laser beam is weaker than the thickness of the tissue.
3. The brain tissue possesses a uniform refractive index; light across the middle in a direct line until it is either diffused or absorbed.
4. The boundary of the tissue are smooth and reflective according to the law of Fresnel; it is for this reason that we exhibit first a preview on the radiative transfer in this biologic middle, while developing a mathematical model that will allow us to diagnose an anomalous in the sample and then, quantify reliable results using a numerical model suitable.

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 $(r_0, \theta_0, \varphi_0)$. 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 Fig.1.

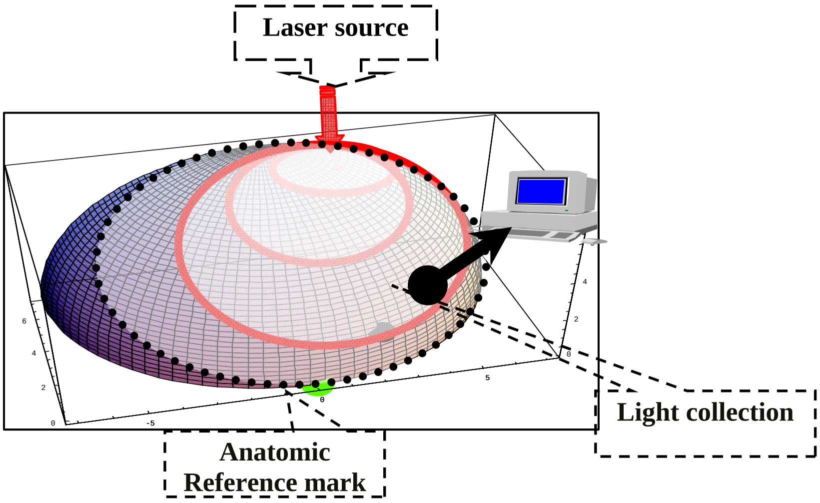

Fig. 1 Distribution of laser light in a spherical tissue [6]

The volume explored by the pair source - detector placed on the surface of the tissue, is a packet curved with an average depth of ¼ of the distance between the source and the detector [7] (see Fig.2).

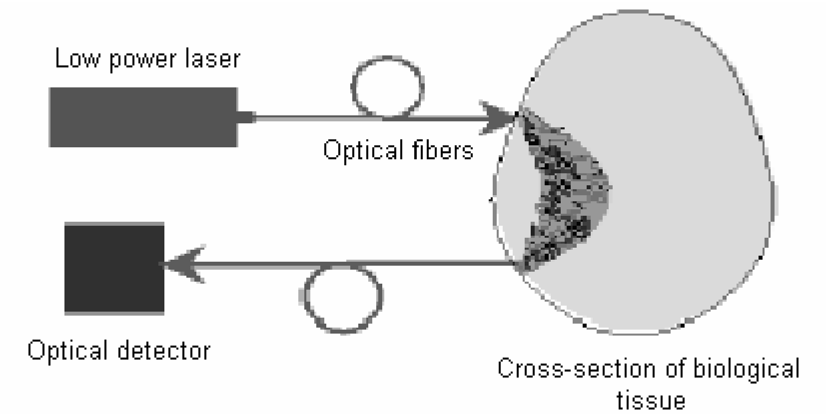

Fig. 2 Shape of the photon bundle through tissue in reflection geometry

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 [8]:

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

Several mathematical models have been used from this integral-differential equation to describe the propagation of light in a turbid medium.
The most simple equation is called diffusion equation; it is expressed by [9]:

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

With diffusion constant [10]:

$$D = 1/3(\mu_a + \mu_s') \qquad (3)$$

The reduced scattering coefficient is expressed by [11]:

$$\mu_s' = (1-g)\mu_s \qquad (4)$$

S: luminous point source in time and space and irradiating a homogeneous human brain.

A solution to this problem corresponds to the formulas given by Patterson, but which remains no valid for the interfaces [11].
When the light strikes a particle of refractive index different from its environment, it is refracted. The angle for which the light is deviated is a function of the size and the shape of the particle and strongly depending on the wavelength and thus the incidence angle. The phase function depends on the angular distribution of the scattering angles [12]. It is noted $p(\vec{s},\vec{s}')$ and described the probability of diffusion of a photon in a direction compared to an initial direction during only one diffusion.
- The anisotropic angular function of Henyey-Greenstein is expressed by [13]:

$$\begin{cases} P_{HG}(\cos\theta) = \dfrac{1-g^2}{2(1+g^2-2g\cos\theta)^{3/2}} \\ p_{HG}(\varphi) = \dfrac{1}{2\pi} \end{cases} \tag{5}$$

Where, $\theta = (\vec{s},\vec{s}')$ is the scattering angle, φ is the azimuth angle of scattering, and g is the average value of the cosine of the scattering angle which describes the anisotropy degree.

B. Basis principle

The Monte Carlo model offers a flexible approach to analyze the light transport in a turbid medium. The behavior of propagation of a photon in the biological tissue structure of the brain can be decided according to two parameters: the mean free path of the event of scattering or absorption, and the scattering angle of the event of diffusion described by Wang and Jacques [4]. The differences between the codes depend on the recording of fluence of the photons during Monte Carlo simulation. At the beginning, the initial position and the direction of the photon are defined. The source can be diverging, as defined by the source numerical aperture *(NA)*, in which case the azimuth angle is determined by a random number uniformly distributed from 0 to 2π.
Given the initial position and direction of the photon, the length to the first scattering event is calculated from an exponential distribution. Absorption of the photon is considered by decreasing the photon weight by $exp(-\mu_a/L)$, where μ_a is the absorption coefficient and L is the length of the way traveled by the photon [4]. The photon moves this length. A scattering angle is calculated using the probability distribution given by the Henyey-Greenstein phase function described above. A new scattering length is then determined from an exponential distribution. The photon spreads through this new length in a new direction. This process continues until the photon leaves the medium or dies. When the photon tries to leave the medium, the probability of an internal reflection is calculated using the Fresnel equation [4].

$$R(\theta_i) = 0.5 \times \left[\frac{\sin^2(\theta_i - \theta_t)}{\sin^2(\theta_i + \theta_t)} + \frac{\tan^2(\theta_i - \theta_t)}{\tan^2(\theta_i + \theta_t)} \right] \tag{6}$$

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

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

$$n_i \sin\theta_i = n_t \sin\theta_t \tag{7}$$

If a reflection occurs, then the photon is retrodiffused in the medium 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:
- The photons are launched from an isotropic point source of unit power $P = 1mW$ inside a homogeneous medium [4].
- The medium has optical properties of absorption, scattering and anisotropy.
- To study : 1-the stationary distribution of the relative rate of flow $F/P(cm^{-2})$, where F represents the fluence $(W.cm^{-2})$, 2-the Fresnel reflectance R_f, 3-the Fresnel transmittance T_f, and 4-the number of photons collected at the surface of tissue.

- During each step of propagation, when the photon is propagated, it deposits a fraction of its weight inside a *"bin"* which corresponds to its position.
- Each *"bin"* in a vector of binarization accumulates the weight of deposited photon due to absorption of all the *"N"* photons in the "bin" *[A [ir]]*.
- After having propagated all the *"N"* photons, each vector matrix *A[ir]* contains a weight accumulated of absorbed photons.
- By dividing each vector matrix *A[ir]* by the total number of photons *"N"* and by the volume of this *"bin" V[ir]*, so we get the concentration $C[ir](cm^{-3})$ of the absorbed photons [14]:

$$C[ir] = A[ir]/(N \times V[ir]) \tag{8}$$

- By dividing *C[ir]* by the absorption coefficient $\mu_a(cm^{-1})$, we get the relative rate of the luminous flow [15]:

$$F[ir] = C[ir]/\mu_a \tag{9}$$

3. Monte Carlo algorithm

The principle of this digital 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 medium: to work with the spherical coordinates.
- The distance of the light propagation is between *0.5cm* and *3cm*.
- Penetration depth of the photon *NIR* is [16]:

$$\tau = 1/\left(\mu_a + \mu_s^{'}\right) \tag{10}$$

- The distribution of the field of photons depends strongly on the distance source-detector.
- The flight of the photon is given by the following equation [17]:

$$d_{pr} = -\int c dt = c\int_{t_e}^{t_0} \frac{dR(t^{'})}{R(t^{'})} \tag{11}$$

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 [11] (see Fig.3).

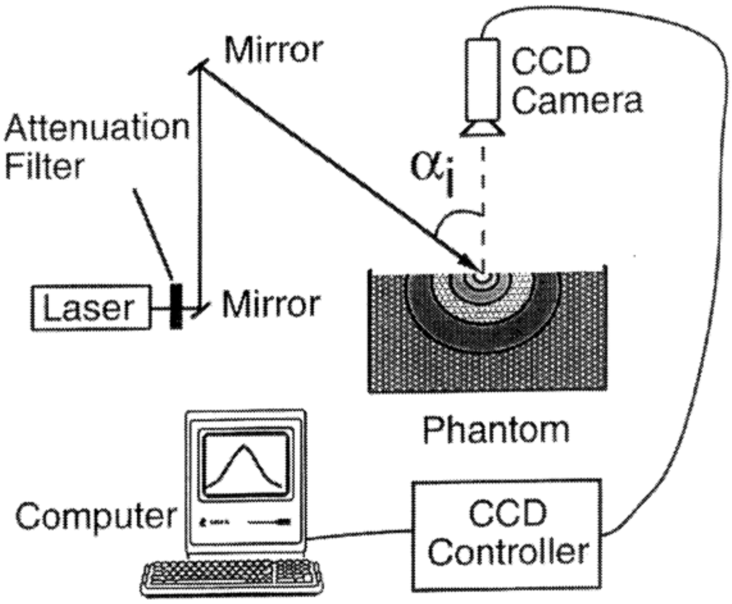

Fig. 3 Experimental device [11]

4. Results and Analysis

In our spherical model, we send 10^5 photons with optical parameters (grey matter) [21] $\mu_a = 0.1cm^{-1}$, $\mu_s = 100cm^{-1}$, $g = 0.9$ and $n = 1.4$ with a radial depth $R = 0.75cm$ and irradiation of *1mW(1 Joule)* for a pulsed time of *20ps* by *binT* (total time = *2ns*) and for binarizations in spherical coordinates r, θ and φ respectively of *0.075cm* 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 (see Fig.4).

We regroup the results calculated by the modified code of Monte carlo at a semi spherical circular surface [7] (see Fig.5). We draw *Photons_r*θ according to *(Pos_r – Pos_*θ*)*, the same for the fluence *F* as a function of the radial positions and respectively the reflectance *R* and the transmittance *T* as a function of the pulsed times *Tps* in picoseconds. We note the existence of a photonic density in the center of the circular medium (close to the positions *Pos_r = 0cm*) but decreases progressively when we move to the center at the positions *Pos_r = 0.42cm*, by scanning the entire surface as a function of the azimuth angle between $-\pi$ and π . We can also see an increase of the photonic density at the edges of the tissue of the positions *Pos_r = 0.75cm* [8].

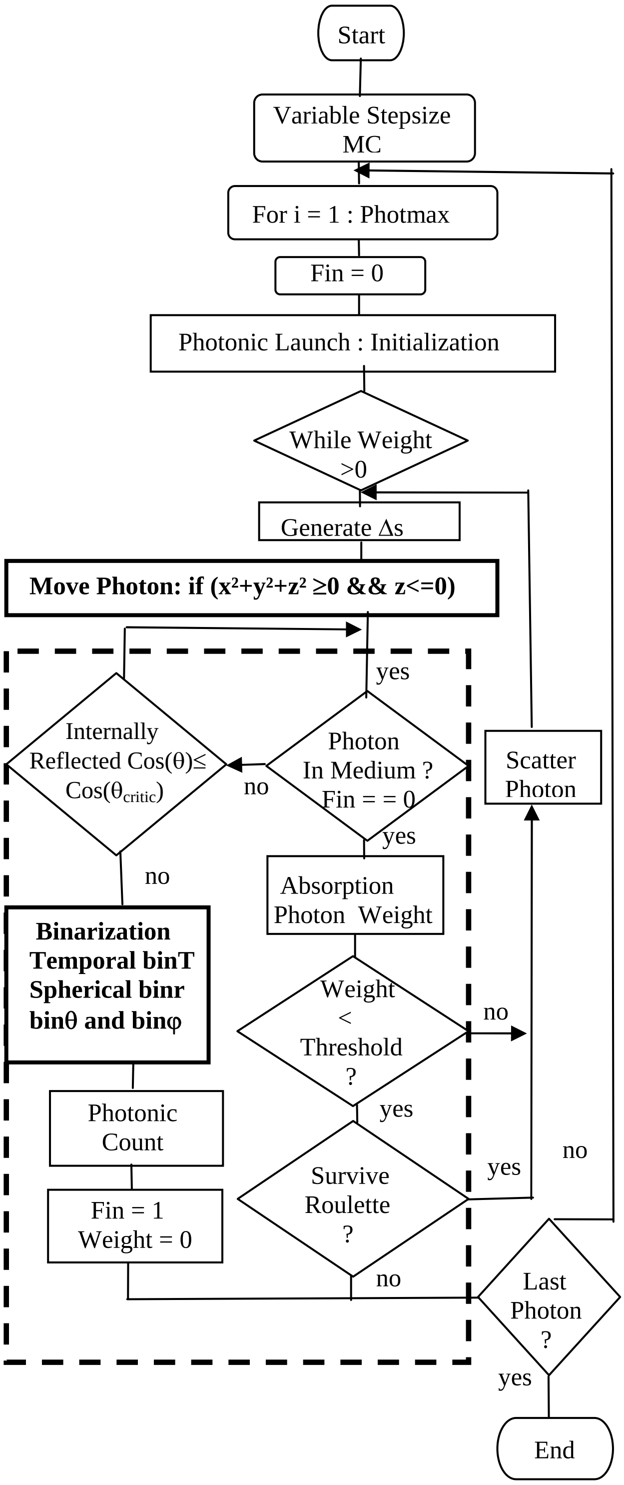

Fig.4 Modified Flowchart for the Monte Carlo code

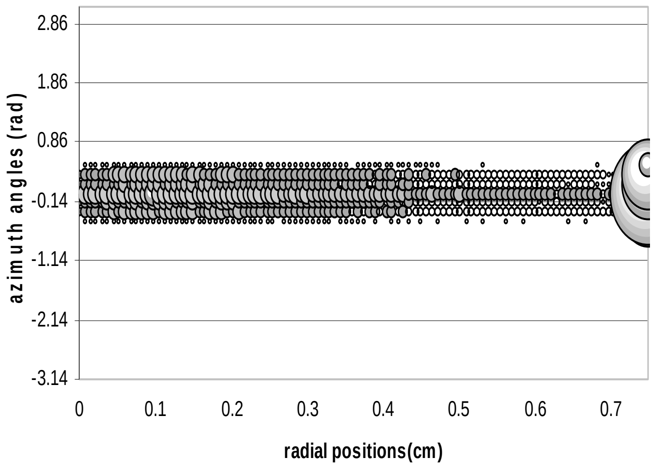

Fig.5 Representation of the photons on a semi-spherical surface according to (r,θ)

Comparing these results with those calculated according to the Cartesian coordinates; the representation in the plane in x and y (see Fig.6), we find a good relationship [19].

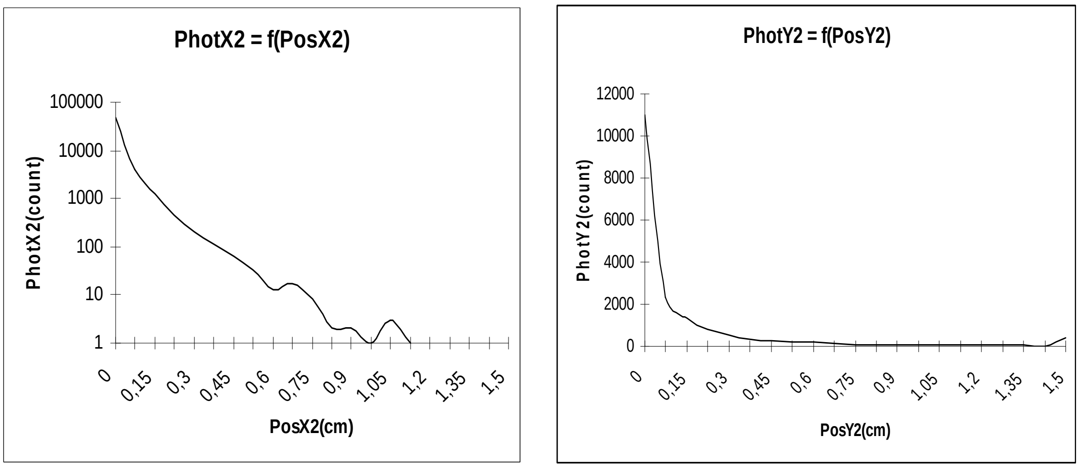

Fig.6 Logarithmic representation of the photons in linear regime according to (PosX,Y)

All these results are validated by the Boltzmann distribution function in linear regime [18]. We send the photons one after the other, and we increment until the number of photons to be injected is reached *(Photons_max)*. We note, that so much that *«W»*, that is to say the weight of the photons is superior to zero, we continue the simulation.

This weight is equal to *one* to the departure, and decreases as the photons enter in the loop to undergo the following events: *move, absorb,* and *scatter*. These are the main phenomena characterizing the propagation of photons in this medium. As soon as the weight reaches the value *zero*, we leave the loop.

We also compare this results with the curves of Fig.7 and Fig.8, giving the transmission and reflection signals as a function of time *T(ps)*, following the same initial conditions. We can affirm a good relationship with a literature. We also note that these graphs present disturbances due to noise in the calculations [20].

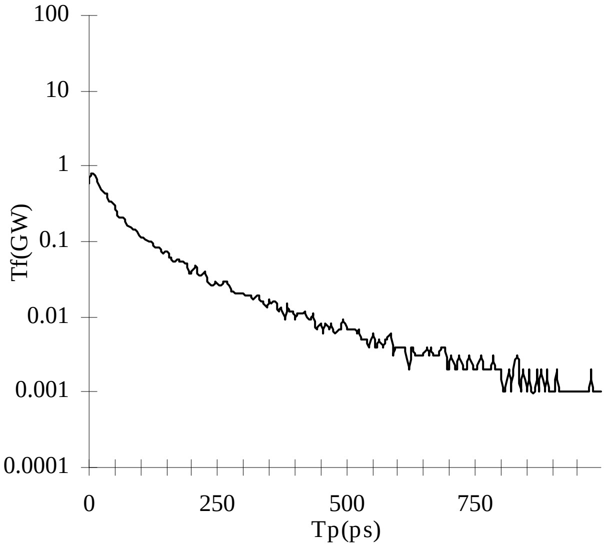

Fig.7 Representation in logarithmic scale of the transmittance according to T_p

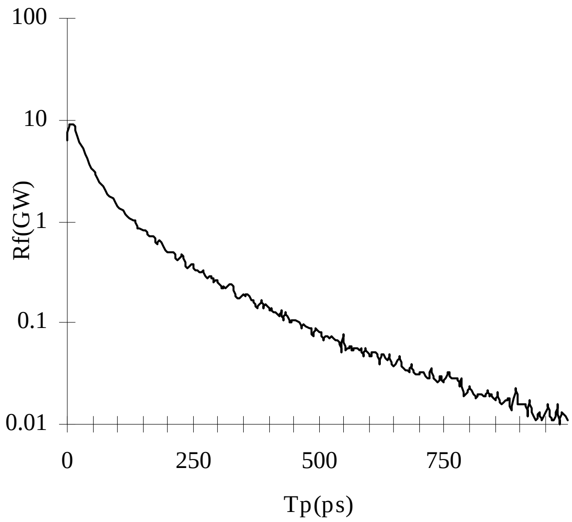

Fig.8 Representation in logarithmic scale of the reflectance according to T_p

5. 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 tissue state and gives 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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