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Research Article

Assessment of Blood Oxygen Saturation by Visible Optical Coherence Tomography Based on Fast Monte Carlo Simulation

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Abstract

A Fast Monte Carlo simulation based on the spectroscopic optical coherence tomography (SOCT) simulated the back reflection of millions of photons in tissues within tens of minutes. Combined with the short time Fourier transform, the reflection intensity at sixteen wavelengths in visible waveband was achieved. The blood oxygen saturation (SO2) was nonlinear fitted through the different absorption coefficients of the oxyhemoglobin and de-oxyhemoglobin at sixteen wavelengths. We designed a model to simulate human retinal blood vessels and measure retinal oximetry. The results showed that the simulation results were consistent with the theory.

Keywords: Spectroscopic Optical Coherence Tomography (SOCT); Fast Monte Carlo Simulation; Fiber Coupler

Introduction

Optical coherence tomography

OCT is a non-invasive, high-resolution, low-damage medical imaging technique developed in the 1990s [1]. The basic principle for OCT is that the low-coherence light passes through a fiber coupler and is divided into two parts, which enter into the reference arm and the sample arm in a Michelson interferometer, respectively. The reference light reflected from the reference arm and the back scattered light from the sample are combined again through the fiber coupler [1-3]. When the optical path difference between the reference arm and the sample arm is within the coherence length of the light source, interference pattern occurs. The intensity of the light signal is obtained by the detector array. Then, the data of the optical signal is sent into a computer for digital image processing to obtain a structural image of the sample. By measuring the time delay of the light reflected at different depths, the axial structure of the sample in depth can be obtained [2-4]. When the beam is scanned or the sample is moved along x-direction and y-direction, three-dimensional images of the sample can be achieved. Further, spectroscopic optical coherence tomography SOCT was proposed to explore the content of the hemoglobin in animal blood. The method of the SOCT is that the broadband interference pattern was segmented and the center wavelength of each part was directed to one absorption coefficient, which changed with the wavelength. Then, by performing the fast Fourier transform to each of the interference spectral signal, a group of three-dimensional images were obtained, which means the reflection intensity at each voxel and wavelength was derived. Compared with the least squares nonlinear fitting, the absorption coefficients can be evaluated in final. A basic SOCT system is shown in figure 1.

The OCT imaging technique has been widely applied to the field of ophthalmology, which plays a very important role in the diagnosis and treatment of human eyes. Due to the low coherence of the broadband light source, OCT has excellent optical slicing ability and can achieve the tomography of the subsurface with high spatial resolution, and the imaging depth of OCT is larger than that of the conventional confocal microscope [3-4]. It can provide retinal

Figure 1: Schematic of a basic SOCT system.

tomographic structure images that are hard observed by the other ophthalmic non-destructive diagnosis techniques, which not only can clearly show the microstructure and pathological changes of the retina, but also can observe and make the numerical analysis quantitatively [3-5].

Monte carlo simulation of OCT

In the practical application of the OCT system, for continuous samples, different ground truths, most of the intensity information reflected by their A-scans are the same [6-8]. Therefore, in practical applications, in order to obtain the most accurate OCT image, we must simulate the tissue model in advance, and obtain the simulated image of the tissue by simulation [6-8].

The Monte Carlo method is based on probability and statistics. Using random numbers, the frequency of an event or the average value of a random variable is used as the solution of the problem [6]. Therefore, the Monte Carlo method is suitable for the simulation process of photon transmission in tissues. A tissue model was prepared and the parameters of the different tissues were arranged, which included absorption coefficient μa (cm-1), the scattering coefficient μs (cm-1), anisotropic factor g and the real refractive index n0 of the tissue [6-8]. By determining the incident position of the photon, the photon/photon packet with the emission weight W = 1 enters the tissue model. Using the parameters of the designed tissue model, the photon takes a random sampling step in the tissue, and the photon absorption and photon scattering occurs [7-9]. Next, checking whether the photon is at the boundary. When the photon is transmitted from the boundary instead of overflowing the tissue, it needs to be calculated according to the tissue parameters of the newly entered layer. When the photon finally overflows the tissue boundary or the remaining weight of the photon is lower than the set threshold, the roulette is used to determine whether the photon is dead. If the photon disappears, the final trajectory and weight information of the photon should be recorded. At the same time, a new photon will emit and its trajectory will be tracked until the last photon is dead and the simulation process ends. The process of the standard simulation is illustrated in figure 2.

Figure 1: Schematic of a basic SOCT system.

Figure 2: Flow chart of the standard Monte Carlo simulation.

Fast monte carlo simulation of OCT

As mentioned in the introduction, the standard Monte Carlo simulation of OCT may take one to two thousand photons to detect one photon, so it takes a lot of time to detect a sufficient number of photons to construct the structure of the tissue [11].

A fast Monte Carlo simulation of OCT used here is based on importance sampling. Importance sampling is an advanced statistical method that consists of basing random events in such a way that the events of interest, which are often rare, appear more often in Monte Carlo simulations [12-16].

The importance of importance sampling applied to Monte Carlo simulation of OCT lies in that biological tissues generally have large anisotropic factor g, and the photon will experience the strong forward scattering when transmitting through the tissue, while the probability of back-scattering is much small. Here, we set a probability bias function for photon scattering, bias the scattered photon packet direction preferentially towards the actual position of the center tip of the collecting optical system, once the photon packet is traveling away from the probe, to increase the probability of the detection. The probability bias function can be adopted by many different function forms. At the same time, in order to reduce the statistical deviation caused by the probability deviation function,

we update the photon weights after each step. The new photon weight should be equal to the probability deviation function multiplied by the original weight. The process of the fast Monte Carlo simulation is illustrated in figure 3.

Figure 3: Flow chart of the fast Monte Carlo simulation.

Simulation results

In order to verify the above fast Monte Carlo simulation program for OCT, we have designed two circles with different diameters to simulate the homogeneous blood vessels located at the surface of the retina, as shown in Figure 4a.

Vessel 1 (left) has a diameter of 0.3 mm and Vessel 2 (right) has a diameter of 0.2 mm. Determine the optical characteristics of the tissues through the wavelength of the simulated incident light: absorption coefficient, scattering coefficient. For example, the SO_2, the total absorption coefficient μ_a and the scattering coefficient μs in the blood was chosen as 85%, 112.0352 cm^{-1}, 43.6 cm^{-1}, respectively. The photon wavelength was used from 500 nm to 650 nm where the absorption of the tissues can be ignored except the hemoglobin in the blood.

Running the above fast Monte Carlo simulation program, the obtained matrix information is processed by post digital image processing to obtain the simulated cross sectional image of the retinal blood vessel as shown in Figure 4b.

Figure 4: (a) Designed two retinal vessels: yellow background is dermis and the red circle are blood vessels; (b) The cross section of two blood vessels simulated from the fast Monte Carlo simulation.

The higher density with the bright spots in the Fig. 4 indicates that these areas have weaker absorption and higher reflection intensity values, and the black shading areas indicate that these regions have stronger absorption and lower reflection intensity values [14-16]. The outline of the designed blood vessel can be clearly seen from the result. It has been demonstrated that the fast Monte Carlo simulation of OCT can be performed within a few minutes. The detection of a sufficient number of photons was completed and the structure of the designed tissue was accurately constructed.

Further, we verified the assessment of the oximetry of the simulated blood vessels by using the fast Monte Carlo simulation program.

It has been studied that when OCT of retinal blood vessels is performed at several wavelengths between 500 – 650 nm where the absorption of the hemoglobin dominates, the reflected light intensity satisfies the Equation below.

$$I^2 = I_0^2 \cdot R_0 \cdot r \cdot exp\,[-2n \cdot d \cdot (\mu_a(HbO_2) \cdot SO_2 + \mu_a(Hb) \cdot (1 - SO_2))] \quad ----(1)$$

Where I_0 is the source spectrum, R_0 is the reflection of the reference arm, n is the mean refractive index of the blood, d is the vessel diameter, $r(\lambda)=A*\lambda^{-a}$, where A is a constant, $\mu_a(HbO_2)$ is the absorption coefficient of the oxyhemoglobin, $\mu_a(Hb)$ is the absorption coefficient of the de-oxyhemoglobin, SO_2 is the oxygen saturation [16-17]. After measuring several intensity information values at different wavelength, the SO_2 can be obtained by the least squares fitting.

In this paper, we simulated 16 waveband segmentations in the visible range spanning from 500 nm-650 nm, while millions of

photons were shined into the tissue. In the simulation program, we modified the optical parameters, such as absorption coefficient μa, scattering coefficient μs of each tissue, to the specific corresponding to the photon wavelength. When the SO_2 concentration of the blood vessel and the starting number of photons are chosen, the fast OCT Monte Carlo simulation above was performed 16 times.

In order to obtain the intensity of the reflection I and the intensity of the light source I0 from the simulated sample, we picked the number of the pixels in the same size of the blood vessel and the topmost dermis, respectively. And the valid number of pixels was measured where the intensity value of the pixel was greater than a predetermined threshold [15-17].

Based on the 16 reflection intensity at each voxel and wavelength, we chosen a specific voxel situating in the blood vessel to analyze the SO_2 by the least squares fitting method, and it can be obtained that the error between the simulated blood SO_2 (88%) and the theoretical value is about 3%, which proves that the simulation is feasible. Both the intensity evaluated from simulation and the intensity from the theory are shown in figure 5.

Figure 5: Comparison of simulated fitting curve and theoretical curve.

Discussion

The fast SOCT Monte Carlo simulation used in the paper can increase the probability of the biased selection and update the photon weights when photons are scattered. In a matter of minutes, a high-precision photon transmission process can be recorded in the tissue.

Also, the simulation results are not hundred percent consistent with the theoretical value of SO_2. Some reasons are taken into account. During the simulation, the anisotropy factor g of the tissue at different wavelengths has not been modified. In fact, the intensity value of the OCT signal will be increased as the anisotropic factor g decreases. In addition, the method used to obtain the signal strength in OCT imaging technique is limited by the depth and the operable pixel area is limited, so that the perfect acquisition of the signal strength cannot be achieved.

The fast SOCT Monte Carlo simulation program used in the paper can be optimized in future, and it will be developed to obtain the deeper and higher resolution imaging. Using the fast SOCT Monte Carlo simulation, the signal processing in the real OCT system is more accurate and convenient. Through the machine learning and the establishment of the large databases, the practical application of the OCT system in the medical field will be more efficient and convenient. Non-professional personnel can accurately obtain the actual structure and information of the organization.

Conclusion

We tested a Fast Monte Carlo simulation based on the SOCT technique, which can simulate the back reflection of millions of photons in tissues within tens of minutes. It mainly adds the probability bias selection during the photon scattering, and updates the weights based on the bias function during scattering. Enough photons that provide valid information on tissue reflections can be detected in minutes. Through the theoretical model testing of the oximetry of the retinal blood vessels, the error between the simulation program result and the theoretical value of the blood SO2 is about 3%, which proves the feasibility of the procedure.

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