Monte Carlo Simulation of Retinal Light Absorption by Infants

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Abstract

Retinal damage can occur in normal ambient lighting conditions. Infants are particularly vulnerable to retinal damage and thousands of preterm infants sustain vision damages each year. The size of the ocular fundus affects retinal light absorption, but there is a lack of understanding of this effect for infants. In this work, retinal light absorption is simulated for different ocular fundus sizes, wavelengths, and pigment concentrations by using the Monte Carlo method. The results indicate that the neural retina light absorption per volume for infants can be two or more times of that for adults.

Keywords: Retinal light absorption; Infants; Monte Carlo simulation

OCIS codes: 170.0170; 170.3660; 290.7050

1. Introduction

Light can cause damage to eyes [1, 2], and retinal damage is the most common type [1]. Retinal damage can happen even when light intensity is modest. Common light sources used for room lighting, phototherapy, ophthalmoscopes, and fundus cameras can all cause retinal damage [3, 4] to which infants are highly vulnerable. Retinal damage is especially common for preterm infants, who are subjected to long-term exposure to nursery light [5-7]. Retinopathy of prematurity (ROP) leads to significant visual impairment and blindness worldwide. Thousands of premature infants lose their sight to ROP each year [8]. ROP can result from various causes. The effect of artificial respiration of premature infants with high concentrations of oxygen and ill-controlled recirculation is considered a major reason; however, high levels of ambient illumination in the hospital nursery are also believed to be a factor for ROP [6, 7]. Existing research on human retinal light absorption focuses on the adult retina. The sizes of infant eyes are different from adult eyes [5], and thus results obtained from adult retinas may not be directly applicable to infants. Nonetheless, there is a lack of research in the literature on how retinal light absorption is affected by the eye sizes of human infants. To better understand ROP and photo-induced retinal damage in infants, there is a need to evaluate the amount of light absorbed by infant retinas.

Monte Carlo simulation has been widely used to study light-tissue interactions. It is considered to be an effective method to investigate photon actions in biological tissues [9-11]. Wavelengths and pigment concentrations affect retinal light absorption and retinal damage [1, 2, 5, 12, 13]. In this work, retinal light absorption of infants was simulated for different wavelengths, pigment concentrations, and ocular fundus sizes by the Monte Carlo method.

2. Method

A basic Monte Carlo simulation process for retinal light absorption can be found in [14]. While photons are propagating inside a tissue, they can be scattered, reflected, transmitted, or absorbed.
Scattering and absorption coefficients are used to determine the movement of a photon on a probabilistic basis [10]. The scattering angles are determined by the Heyney-Greenstein phase function [15]. The Fresnel principle is used to determine whether photons are reflected or transmitted at the boundary of two layers that have different refractive indices. In [9], a Monte Carlo model was developed to study the effects of melanin concentrations on retinal light absorption in adult human and mouse retinas, in which the retinal tissues were modeled as a sphere with five concentric spherical layers: neural retina layer, retinal pigment epithelium (RPE), choroid, sclera, and a semi-infinity-thick tissue layer outside the sclera. In the current work, the 5-layer spherical Monte Carlo model is again employed to study retinal light absorption by human infants as affected by ocular fundus size, pigment concentration, and wavelength. A detailed description of the 5-layer spherical Monte Carlo model can be found in [9].

Each of the layers is characterized by geometrical and optical parameters. Parameter values for the ocular fundus of human infants are lacking. In this work, some parameter values have to be adapted from adult data by multiplying appropriately chosen coefficients. The absorption coefficients of the neural retina layer and sclera layer are obtained from [9] and [16]. The absorption coefficients of the RPE layer and choroid layer are computed based on melanin concentration and hemoglobin concentration as follows [9]:

$$\mu_a^{RPE} = 2.31c_m\varepsilon_m(\lambda)$$ (1)

$$\mu_a^{Choroid} = 2.31c_m\varepsilon_m(\lambda) + 2.31c_b\varepsilon_b(\lambda)$$ (2)

where $\mu_a^{RPE}$ and $\mu_a^{Choroid}$ are the absorption coefficients of RPE layer and choroid layer, respectively; $c_m$ (mol/l) and $c_b$ (mol/l) are the concentrations of melanin and blood, respectively; $\varepsilon_m$ (cm$^{-1}$/mol/l) and $\varepsilon_b$ (cm$^{-1}$/mol/l) are the molar extinction coefficients of melanin and blood, respectively. Melanin in the RPE is a highly active metabolic substance. Disc shedding in the RPE is required for continuous regeneration of the photoreceptors. Lack of melanin may affect the regeneration of photoreceptors and result in receptor damage. This role of melanin is not considered in this work because the focus of this work is light absorption and photo-induced retinal damage. In accordance with [9], two sets of melanin concentrations are used: (1) 4.0 mol/l for the RPE layer and 1.0 mol/l for the choroid layer, and (2) 0.4 mol/l for the RPE layer and 0.1 mol/l for the choroid layer. The normal hemoglobin concentration for adults is 1.73±1.80 mmol/l [9, 14]. In this study, three levels (0.85 mmol/l, 1.7 mmol/l, and 3.4 mmol/l) of hemoglobin concentrations are used. A 95% oxygenation rate of the blood is assumed, i.e., 95% is oxy-hemoglobin and 5% deoxy-hemoglobin [9]. The molar extinction coefficients of melanin and hemoglobin at visible wavelengths have been compiled by Jacques [17]. The refractive index $n$, anisotropy $g$, scattering coefficients are all obtained from previous research [9, 16, 18-20]. The average ocular diameter of infants is set as 17.0 mm [21], which is 70% of adults (24.0 mm) [9]. The average pupil size is set as 3.5 mm [22]. In reality, the pupil size varies over a wide range across subjects and environmental light intensity. Sometimes, the pupil size does not fully adapt to light intensity changes when, for example, the optic nerves are partially damaged (known as bene dilitatism). In some treatments, pupils are dilated. Thus, it is not feasible to use the pupil size to control light entering the ocular fundus for a given age or size of ocular fundus. For easy comparison, photons are assumed to be directly incident on the neural retina layer and neural retina light absorption is recorded as a percentage of light incident on the neural retina layer. According to [21], the neural retina layer thickness of infants is 90% of adult retinas, and the pupil size and the thicknesses of choroid and sclera are 70% of those of adults. There are no available measurements on the RPE layer thickness for infants. It is assumed to be 70% of the adult RPE thickness. According to the adult data, which can be found in Guo et al. [9], the average thicknesses of infant neural retina, RPE, choroid, and sclera are estimated to be 180 µm, 7 µm, 175 µm, and 490 µm, respectively.
These are the average values reported in the literature and are referred to as the standard sizes of ocular fundus in this work.

In order to evaluate the effects of different eye sizes on retinal light absorption, a size growth factor $f$ is used to compensate for eye development, by which the thickness of the neural retina layer can be expressed as a function of standard size as:

$$d_{\text{Neural retina layer}}=180\times(1+\beta f)$$

and the sizes of other ocular fundus parameters (thickness of RPE, choroid, sclera, pupil size, and ocular fundus diameter) can be expressed as a function of standard size as:

$$d_{\text{others}}=\text{average size}\times(1+f)$$

where $f\leq 100/70-1$, $\beta$ is a coefficient of the growth rate difference between the thickness of neural retina layer and the sizes of other ocular tissues. When $f=0$, the sizes of the infant eyes are standard; when $f=0.429$, the sizes have reached the average values of adults; when $f<0$, the sizes are smaller than the standard sizes for infants. In order for the thickness of the neural retina layer and the sizes of other ocular tissues to reach adult sizes at the same $f$ value (0.429), $\beta$ should be equal to $(1/9)/(3/7)=0.259$. In this work, the range of $f$ is set as $-0.4\leq f\leq 0.4$ to cover a wide range of eye sizes. The refractive indices, anisotropy, and average thickness of each layer are listed in Table 1. The absorption coefficients and scattering coefficients of the neural retina layer, RPE layer, choroid layer, and sclera layer are shown in Figures 1 and 2. The outermost layer is modeled as a typical background with an absorption coefficient of 0.1 cm$^{-1}$, a scattering coefficient of 100 cm$^{-1}$, and an anisotropy coefficient of 0.9 [9, 23].

**Table 1** Refractive indices, anisotropy, and thickness of the fundus of human infants [9, 21-23].

<table>
<thead>
<tr>
<th>Layer</th>
<th>Refractive Indices</th>
<th>Anisotropy</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitreous &amp; inner limiting membrane</td>
<td>1.336</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Neural retina layer</td>
<td>1.47</td>
<td>0.97</td>
<td>180</td>
</tr>
<tr>
<td>RPE</td>
<td>1.47</td>
<td>0.84</td>
<td>7</td>
</tr>
<tr>
<td>Choroid</td>
<td>1.47</td>
<td>0.87</td>
<td>175</td>
</tr>
<tr>
<td>Sclera</td>
<td>1.47</td>
<td>0.9</td>
<td>490</td>
</tr>
<tr>
<td>Tissue background outside the sclera layer</td>
<td>1.36</td>
<td>0.9</td>
<td>$+\infty$</td>
</tr>
</tbody>
</table>
Figure 1 Absorption coefficients of the neural retina layer, RPE layer, choroid layer, and sclera layer (RPE melanin; 4 mol/l; choroid melanin, 1 mol/l, choroid hemoglobin, 1.7 mmol/l)
Figure 2 Scattering coefficients of the neural retina layer, RPE layer, choroid layer, and sclera layer

As in [9], the incident photons are initialized uniformly across the neural retina layer within an azimuth angle of 60°. The incident angular profile at the neural retina surface is assumed to follow the Lambertian distribution, which implies that the incident intensity is proportional to the cosine of the incident angle. Photons exiting from the neural retina layer into the vitreous cavity may reenter the neural retina layer depending on the exit angle. A photon may be completely absorbed inside the tissue or exit through the pupil of a predefined size. Changes in the refractive index may cause photon reflection. A total of $10^6$ photons are used when melanin concentration in the RPE is less than 0.4 mol/l and $4 \times 10^9$ photons are used when melanin concentration in RPE is higher than 0.4 mol/l. This ensures that the standard deviation of the Monte Carlo simulation is less than 0.1% of the mean value.

3. Results and Discussion

3.1. Neural retina light absorption changes with different eye sizes and wavelengths at high and low pigment concentrations

Figure 3 shows the percentage of total neural retina light absorption for different eye sizes and wavelengths. For all wavelengths, when pigment concentrations are lower (Figure 3a), the percentage of light absorbed by the neural retina layer is higher because fewer photons are absorbed by the RPE and choroid layers, where the pigments are present. As eye sizes increase from the smallest ($f=-0.4$) to the largest ($f=0.4$), total neural retina light absorption increases by approximately 30%. This makes sense because the neural retina layer is the top layer. A larger size will trap photons inside the neural retina layer for longer paths, which results in higher absorption. This means that the total neural retina layer light absorption rate for adults is higher than that for infants. To evaluate the potential of heat damage to the neural retina layer, the total neural retina light absorption should be normalized by the volume of the neural retina layer. The relative neural retina light absorption per unit volume is shown in Figure 4. Figure 4 clearly shows that neural retina light absorption per unit volume is higher when the eye is smaller in a broad range of pigment concentrations and wavelengths. The results show that infant neural retina light absorption per unit volume is two or more times that absorbed by the adult neural retina layer for all wavelengths.
Figure 3 Percentage of total neural retina light absorption for different eye sizes and wavelengths. (a) hemoglobin concentration is 0.85 mmol/l, melanin concentration in RPE is 0.4 mol/l, melanin concentration in choroid is 0.1 mol/l; (b) hemoglobin concentration is 3.4 mmol/l, melanin concentration in RPE is 4 mol/l, melanin concentration in choroid is 1 mol/l.

Figure 4 Percent neural retina light absorption per unit volume at different eye sizes and wavelengths. (a) hemoglobin concentration is 0.85 mmol/l, melanin concentration in RPE is 0.4 mol/l, melanin concentration in choroid is 0.1 mol/l; (b) hemoglobin concentration is 3.4 mmol/l, melanin concentration in RPE is 4 mol/l, melanin concentration in choroid is 1 mol/l.

3.2 Variation of percent neural retina light absorption per unit volume with eye size

Figure 5 shows the variations of percent neural retina light absorption per unit volume with eye sizes for three typical wavelengths: (a) 510 nm; (b) 550 nm, and (c) 630 nm. The neural retina light absorption per unit volume for infants can be 5 or more times that of adults when \( f = -0.4 \). Even for the standard size of infant retina, the light absorption per unit volume is twice that of adults. This means that photons incident on the neural retina layer will produce several times more heat per volume in the neural retina layer of infants, which might contribute to the high rate of ROP in premature infants. Figure 5 also shows that hemoglobin concentration variations do not affect neural retina light absorption when the melanin concentration in the RPE is 0.4 mol/l and that in the choroid is 0.1 mol/l or higher. This implies that albino retinas are more vulnerable to environmental light damage because the role of melanin cannot be replaced by other pigments.
Figure 5 Percent neural retina light absorption per unit volume for different eye sizes. (a) 510 nm; (b) 550 nm, and (c) 630 nm. H0.5, H1.0, and H1.5 indicate hemoglobin concentration in the choroid layer being 0.85, 1.7, and 3.4 mmol/l, respectively. M0.1 shows melanin concentrations of 0.4 mol/l in the RPE and 0.1 mol/l in the choroid; and M1.0 indicates melanin concentrations of 4 mol/l in the RPE and 1 mol/l in the choroid.

3.3 Variation of neural retina light absorption with wavelength

Figure 6 shows the percent neural retina absorption per unit volume as a function of wavelength for three different eye sizes: small size ($f=-0.4$), standard infant eye ($f=0.0$), and large size ($f=0.4$); and high and low melanin concentrations. The results show that eye size has a significant impact on neural retina light absorption at all wavelengths. Neural retina light absorption is extremely high in the region of 450 nm or lower and around 550 nm. Blue photons have higher energy than photons of longer wavelengths. This may explain why blue light is more dangerous to infants, especially to premature infants. Melanin plays an important role in neural retina light absorption. Because the neural retina layer is the top layer, melanin will not affect absorption of the incident light by the neural retina layer, but it will affect absorption of backscattered light from the lower or deeper layers. The backscattered light will not only contribute to the heat produced in the neural retina layer but will also reduce the effective contrast of the retinal image because backscattered light is random. Figure 7 shows the percent neural retina light absorption per unit volume of backscattered light at low and high melanin concentrations when $f=0.0$ and the concentration of hemoglobin concentration is 1.7 mmol/l. The simulations clearly show that the backscattered light absorption per unit volume is much higher when the melanin concentration is lower. The values of neural retina light absorption for three eye sizes, three wavelengths, and two pigmented concentrations are listed in Table 2.

Figure 6 Percent neural retina light absorption per unit volume as a function of wavelength. M0.1 shows melanin concentrations of 0.4 mol/l in the RPE and 0.1 mol/l in the choroid; and M1.0 indicates melanin concentrations of 4 mol/l in the RPE and 1 mol/l in the choroid. f-0.4, f0.0, and f0.4 show size growth factor f being -0.4, 0 (standard infant eye sizes), and 0.4, respectively.
Figure 7 Percent neural retina light absorption of backscattered light per unit volume. (a) hemoglobin concentration is 1.7 mmol/l, melanin concentration in RPE is 0.4 mol/l, melanin concentration in choroid is 0.1 mol/l; (b) hemoglobin concentration is 1.7 mmol/l, melanin concentration in RPE is 4 mol/l, melanin concentration in choroid is 1 mol/l.

Table 2 Neural Retina light absorption for three eye sizes, three wavelengths, and two pigmented concentrations (M0.1 shows melanin concentrations of 0.4 mol/l in the RPE and 0.1 mol/l in the choroid; and M1.0 indicates melanin concentrations of 4 mol/l in the RPE and 1 mol/l in the choroid.).

<table>
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<tr>
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<th>Size growth factor f</th>
<th>wavelength</th>
<th>Total absorption (%)</th>
<th>Backscattered absorption (%)</th>
<th>Absorption per volume</th>
<th>Backscattered / Total (%)</th>
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<tr>
<td>M0.1</td>
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<tr>
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4. Conclusion

Retina light absorption for different ocular fundus sizes, wavelengths, and pigment concentrations is simulated. The neural retina light absorption per unit volume for infants can be two or more times that for adults. This may contribute to the high rate of photon-induced retinal damage in infants, especially preterm infants. The simulation results show that the small size of infant ocular fundus should be considered in lighting intensity selection for protection of infant vision from photon-induced retinal damage. Special attention should be paid when an infant pupil is dilated for treatment or diagnosis. Experimental data are warranted to validate the simulation results in future research.

References