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# TEMPERATURE DISTRIBUTION DURING DYE-ENHANCED LASER PHOTOCOAGULATION OF CHOROIDAL FEEDER VESSELS IN TREATMENT OF AMD-RELATED CHOROIDAL NEOVASCULARIZATION (CNV)

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## Introduction

Among all the ocular diseases, age-related macular degeneration (AMD) is the most common cause of vision loss in the United States in patients aged 65 years and older. It is an unpredictable disease that destroys the macula, the area of the retina responsible for central and color visions.

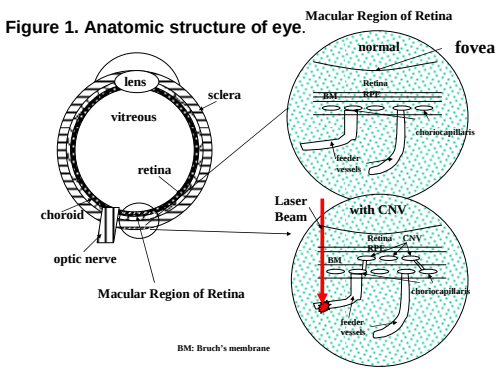
The anatomic structure of eye is three-dimensional and consists of different layers of structure tissues, including the vitreous, retina, retina pigment epithelium (RPE), choriocapillaris, choroidal feeder vessels, and sclera. Figure 1 shows the normal and patho-physiologic anatomic description of the AMD-related tissue structure in eyes. In the healthy human eye, the central region of retina (~ 200 μm dia.) is called macula. Since the macula is avascular, all the nutrients to the macula are supplied by the underneath choriocapillaris, which is a thin 2-D meshed vascular structure. The choriocapillaris is supplied by several larger choroidal feeder arterioles and drained by choroidal feeder venules. The major morphological change of AMD is the formation of a vasculature between the macula and choriocapillaris. The abnormal growth of the vasculature, called the choroidal neovascularization (CNV) is the main reason of interruption of transport of nutrients and wastes between the macula and choriocapillaris.

Among all treatments, laser photocoagulation is recommended. However, direct and contiguous laser treatment to the entire sub-foveal lesion almost invariably damages the foveal and macular region. It is always associated with a substantial and immediate loss of central vision following the treatment.

Indocyanine green (ICG) dye angiography is a clinical tool in the diagnosis and management of CNV membranes secondary to AMD. ICG dye bolus is delivered to the eye via venous injection and reaches the large diameter choroidal vessels, the choriocapillaris, the CNV and the retinal vessels at different times. The infrared absorption and emission spectra of ICG dye enable the visualization and identification of the CNVs and their feeder choroidal vessels, having diameters of 50 μm or less.

In this study we evaluate the temperature field in the vicinity of a targeted feeder vessel during indirect laser therapy. As shown in Figure 1, laser beam is aimed at a choroidal feeder vessel rather than the sub-foveal CNV directly. The hypothesis of this technique is to use laser to manipulate the pressure field in the choriocapillaris and thus, to minimize the driving force (pressure) to the CNV membrane. Decrease in the pressure field leads to a reduction of the blood flow in the CNV. Since the location of the laser focus spot on the feeder vessel is away from the fovea, it is expected that the damage to the RPE in the macular region is minimized.

**Figure 1. Anatomic structure of eye.**



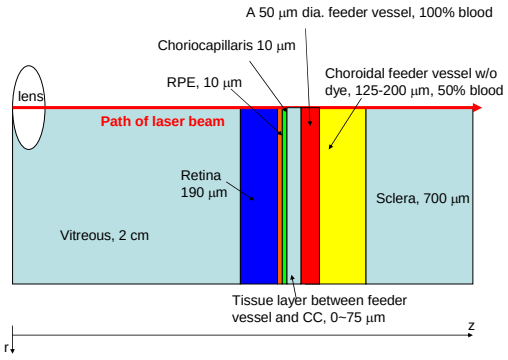

ICG dye has an absorption peak near 800 nm wavelength which is very close to the emission peak of the diode laser (805 nm) used for

the photocoagulation. The existence of dye in the blood should enhance the laser energy absorption if the laser is applied when the dye bolus reaches the targeted vessel. In this study, a heat transfer model is developed to simulate the temperature elevation in the vicinity of a choroidal feeder vessel during dye-enhanced laser photocoagulation. This research focuses not only on the efficiency of ICG dye-enhancement in temperature elevation, but also on the collateral damage to the RPE along the laser path.

## Methods

Figure 2 shows a simplified 2-D geometry of the eye along the laser path. Laser beam passes the central line of the 2-D geometry and temperature elevation occurs in all layers along the laser path. Since RPE has different thermal absorption properties from that of retina, it is modeled as an individual layer of 10 μm in thickness. As shown in Figure 1, the choroidal feeder vessel (50 μm in diameter) usually rises obliquely to the choriocapillaris layer (~10 μm). Thus, in this study the tissue associated with the targeted choroidal feeder vessel is simplified as a layer of 50 μm that is separated from the bottom of the choriocapillaris by a tissue layer (0 ~ 75 μm). The gap between the choriocapillaris and the feeder vessel is filled with tissue. The rest of the choroid is modeled as a single layer filled by 50% of blood and 50% tissue.

**Figure 2. Simplified theoretical model of the eye structure.**




The two-dimensional Pennes bioheat equation in cylindrical coordinate system is used to model the temperature elevation in each layer and is given by

$$\rho c \frac{\partial T_t}{\partial t} = k_t \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_t}{\partial r}\right) + k_t \frac{\partial^2 T_t}{\partial z^2} + q_{laser} + \omega_b \rho_b c_b (T_a - T_t) \quad (1)$$

where ρ is density, c is specific heat, $T_t$ is temperature of each layer, $T_a$ is arterial blood temperature of 37°C, and $q_{laser}$ is the volumetric heat generation (W/m$^3$) modeling the laser energy absorption in the layer.

During laser treatment the volumetric heat generation term in the above equations is due to laser light scattering and absorption in tissue and the decrease in a monochromatic beam of irradiance, $I_{\lambda,0}$, can be described by the Beer's law, $I_{\lambda,z} / I_{\lambda,0} = e^{-\mu z}$ (2)

where $I_{\lambda,z}$ (W/m$^2$) is the irradiance distribution at location z and is assumed to be the Gauss distribution in the radial direction, and $\mu$ is defined as the attenuation coefficient that is determined by both absorption and scattering in the tissue. Therefore, the volumetric heat generation in the tissue, $q_{laser}$ (W/m$^3$), is calculated as

$$q_{laser} = E_0 e^{-r^2/W_L^2} \mu e^{-\mu z} \quad (3)$$

where $E_0$ is the maximum irradiance at the entrance plane of each layer and is related to the total laser power $Q$ and energy absorption in the previous layers, and $W_L$ is the $1/e^2$ radius of the laser beam.

## Results

Table 1 lists the geometrical parameters, radiation properties, and local blood perfusion rate of each layer used in the model. Detailed temperature profiles along the central line of the laser path are given in Figures 3a and 3b for normal and ICG dye-enhanced conditions, respectively. It is evident that the ICG dye-enhanced energy absorption not only results in a higher temperature elevation in the feeder vessel (725 vs. 570°C), but also shifts the maximal temperature from the sensitive RPE region to the targeted feeder vessel. The ratio of temperature rise in the RPE to that in the feeder vessel, $\beta = \Delta T_{RPE} / \Delta T_{feeder}$ is introduced to evaluate collateral damage occurring in the RPE. Based on the data given in Figures 3a and 3b, one can calculate that $\beta$ decreases from 0.98 in normal conditions to 0.88 in dye-enhanced conditions. We believe that the dye-enhanced laser therapy would significantly reduce collateral damage to the sensitive RPE.

**Table 1. Geometrical parameters and optical properties**

| | $h$ (m) | $\mu$ (1/m) | $\omega$ (1/s) |
|---|---|---|---|
| **Vitreous** | 0.02 | 2.56 | 0 |
| **Retina** | 0.00019 | 725 | 0.005 |
| **RPE** | 0.00001 | 14000 | 0.005 |
| **Choriocapillaris** | 0.00001 | 2040 | 0.167 |
| **tissue** | 0 ~ 0.000075 | 725 | 0.0005 |
| **choroid feeder vessel** | 0.00005 | 4610 (w/o dye), 9000 (with dye) | 0 |
| **Choroid** | 0.000125 ~0.0002 | 3500 | 0.005 |
| **Sclera** | 0.0007 | 506 | 0.00046 |

**Figure 3a. Normal condition (no dye), Q=0.5 W, spot 50 μm dia. Tissue layer between feeder vessel and CC is 25 μm.**

Temperature distribution along the laser beam center line (r=0) in the vicinity of RPE, choriocapillaris (CC) and the choroidal feeder vessel. **The maximum temperature occurs in RPE.**

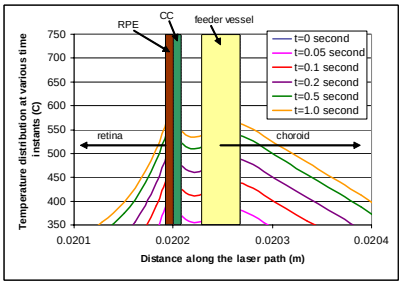



**Figure 3b. Dye-enhanced absorption in the feeder vessel , Q=0.5 W, spot 50 μm dia. Tissue layer between feeder vessel and CC is 25 μm.**

Temperature distribution along the laser beam center line (r=0) in the vicinity of RPE, choriocapillaris (CC) and the choroidal feeder vessel. **The maximum temperature occurs in the feeder vessel. This may be due to the dye-enhanced absorption and the higher temperature in choroid than in retina.**