Modelling laser interaction with retinal tissue at the cellular level

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Ophthalmology has utilised lasers since the 1960s to diagnose and treat many eye disorders. The growing number of laser-medical applications increases the need to understand laser-tissue interaction quantitatively. A critical factor is understanding tissues' heating and thermal conductance characteristics during laser surgery to minimise associated risks. While thermal models have been developed for the human eye, few have been at the cellular level or involving complex spatial structures. This work explores the feasibility of simulating heat transfer for a single laser irradiated retinal cell in 3D, with a focus on a novel methodology to represent laser intensity decay for complex structures with sub-micron resolution.

The basic structure of the cell includes the cell wall, nuclei, cytoplasm (similar absorption property to water) and other organelles which can be sub-divided into: absorbers with high absorption capacity (e.g. melanosome, lipofuscin, etc.), and non-absorbers with absorption similar to cytoplasm (e.g. mitochondria). The general heat transfer equation in the time domain is utilized and described by $\rho C_p \frac{\partial T}{\partial t} + \rho C_p \boldsymbol{v} \cdot \nabla T = -\nabla \cdot \boldsymbol{q} + Q$ where ρ is the tissue density, C_p the specific heat, T the absolute temperature, $\boldsymbol{v}$ the linear fluid velocity vector, and $\boldsymbol{q}$ the heat flux. Q represents the heat source power density which can be described by $Q = I(z)\alpha$, where $I(z)$ is the laser intensity in space and α (m^{-1}) is the material absorption coefficient. In a homogeneous medium (constant α), the optical intensity decays exponentially with the propagation distance (for intensity not affected by beam divergence, scattering and reflections). Assuming absorption dominates scattering, intensity decay over the cell layer can be described by the Beer-Lambert law as $I(z) = I_0 e^{-\int \alpha z \, dz}$, where I_0 is the initial intensity entering the tissue layer and z is the propagation distance. Assuming α is constant in each organelle, the PD form of the Beer-Lambert law equation can be expressed as $\frac{d^2 I}{dz^2} + \left(\alpha^2 - \frac{1}{\alpha}\frac{d\alpha}{dz}\right) = 0$.

This work proposes the novel use of the "Diffusion with convection PDE" mathematical formulation as a means to represent the Beer-Lambert intensity decay. The diffusion-convection equation describes the rate of change of a scalar quantity in a differential control volume given by flow and diffusion into and out of that volume along with any generation or consumption. The general form of the diffusion-convection equation can be described as $\frac{dc}{dt} + \nabla \cdot (-D\nabla c + \boldsymbol{v}c) = R$, where c is the species concentration for mass transfer, t is time, D the diffusivity, $\boldsymbol{v}$ the flow velocity, and R is the net volumetric source for c. In steady–state mode, $\frac{dc}{dt} = 0$, and the equation converts into $\nabla \cdot (-D\nabla c) + \boldsymbol{v} \cdot \nabla c = R$, which is the same form as the 3D extension of the PDE of the Beer-Lambert law. As such, it is feasible to describe the heat equation combined with the intensity decay throughout the layers of retinal tissues by substituting the concentration c for the intensity I, and using $\boldsymbol{v} = \left(0,0,\alpha^2 - \frac{1}{\alpha}\frac{d\alpha}{dz}\right)$, $R = 0$ and $D = -1$. The results of this approach to represent the laser absorption utilising COMSOL 3.5a FEA for pulsed laser treatment of the human eye retina will be presented.