The Thermal Response of Biological Tissue Subjected to Short-Pulsed Irradiations

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Abstract: A combined transient radiation and hyperbolic heat conduction model is developed to predict heat transfer of biological tissue subjected to short pulsed irradiations. Grid systems are compared and simulation results are compared with the experimental data.

1. Introduction

The most easily quantified and commonly observed mechanism is the photo thermal effect in laser tissue interaction [1]. The application of photo thermal effect is laser surgery [1], laser peri-implant treatment [2],laser induced interstitial thermotherapy [3], and so on. The focused laser beam is often used to ablate tumor tissue selectively [4] by irradiating tumor. In this paper, the hyperbolic conduction equation is introduced for the heat transfer model. Furthermore, nonuniform grid system is employed to accurately capture the focused laser beam movement.

2. Mathematical Models

2.1 Governing Equation

The pulses of a focused laser beam are incident tissue into 2 mm below the tissue surface as shown in Fig.1. Three layered tissue is modeled with inhomogeneity medium. The tissue optical and properties are summarized in the table 1.

The heat transfer model is formulated as a two dimensional axisymmetric model as:

$$\rho C_p \frac{\partial T(r,z,t)}{\partial t} = -\nabla \cdot \left[q_{cond}(r,z,t) + q_{rad}(r,z,t) \right] \quad (1)$$

where ρ is the density, C_p is the heat capacity, , T is the temperature, $\mathbf{q}_{cond}$ is the conductive heat flux vector, and $\mathbf{q}_{rad}$ is the divergence of radiative heat flux vector. In hyperbolic thermal wave theory, the conductive heat flux vector is expressed by [5]:

$$\tau \frac{\partial \mathbf{q}_{cond}(r,z,t)}{\partial t} + \mathbf{q}_{cond}(r,z,t) = -k \nabla T(r,z,t) \quad (2)$$

where the thermal relaxation time τ and thermal conductivity k are introduced. Introducing the thermal diffusivity $\alpha = k/\rho C_p$, the speed of thermal wave is

$$c_t = \sqrt{\alpha / \tau} \quad (3)$$

Eq. (2) regresses to the traditional Fourier expression when $\tau \to 0$, and $c_t \to \infty$. To achieve the radiative heat flux vector, transient radiative transfer equation is solved with a 10 ps irradiation. Detail equations and solution technique about it were introduced previous paper works [5].

2.2 Numerical schemes

The Transient Discrete Ordinate Method (TDOM) is adopted to solve the transient radiative transfer equation and the MacCormack's predictor-corrector scheme is employed to solve the hyperbolic conduction equation. In current paper work, the influence of grid systems is highlighted. For the uniform grid system, both radial and axial distances are evenly divided. Two kinds of nonuniform grid systems are implemented as:

$$R_{i+1} = R_i + \Delta R \quad (4a)$$

$$\Delta R_i = \alpha_r \left(\beta_r - \exp\left(-\frac{\gamma_r\, i}{N}\right) \right) \quad (4b)$$

Z directional grid is implemented as a similar manner of radial direction. The grid parameters selected as below:

(Nonuniform gridI) α_r=0.0328; β_r=2;γ_r=10;N=201

(Nonuniform gridII)α_r=0.0427;β_r=1.2;γ_r=25; N=201

The fine grid is employed in the laser beam deposition area and coarse grid is employed to other region. The total number of grid is same as the uniform grid system, which means the calculation cost is not sacrificed.

3. Results and discussion

The simulation results are compared with experimental data [1]. For the experimental study, Q-switched short pulsed Nd:YAG laser operates at a wavelength 1064 nm. The average power of laser is 1.3 W. The temperature predication and measurement data at 10 sec is shown in Fig. 2. In Fig.2 (a), the predication result with nonuniform grid systems show the closer value with the experimental one rather than uniform grid system, especially peak temperature location. It seems no significant difference between nonuniform grid systems. The prediction of maximum temperature increment is most important in the laser surgery because it is the key parameter to estimate of ablation efficiency. The thermal wave damping motion is predicted in the simulation model. Initially, the high temperature gradient takes place between epidermis and dermis tissue region. The epidermis has high light absorbing characteristics, which causes the strong temperature concentration field. As time advancing, the thermal wave moves inside tissue phantom. The thermal wave speed is dependent on the thermal relaxation time, τ. Even though its value has been measured for biological media such as bologna meat samples [1], the exact

Value of thermal relaxation time (typically having values in the range of 5-100 sec) is known for most of the tissues. For this simulation model, the thermal relaxation time is selected as a 17 sec. The radial temperature distribution at Z = 2 mm below the tissue surface is depicted in Fig. 2(b). As similar with the axial temperature behavior, the prediction result with nonuniform grid systems are well matched with experimental one. At R = 0, the prediction of temperature is underestimated about a 3 °C using the uniform grid system. Again temperature increment of 43°C, from the initial temperature 37°C can sufficiently irradiate tumor tissue at the focusing region. The thermal damage area can be localized within approximately 1 mm distance from the focal region using the focused laser beam. In Fig. 3, the contour of temperature field at certain time instant is depicted. The temperature field is mostly confined in the focal region and epidermis tissue region. As time passing, the temperature field is enlarged and the thermal wave propagation is shown. If the irradiation time reaches to the 20 sec, the thermal damage can occur in the health tissue region. The irradiation time then should be selected cautiously.

4. Figures and tables

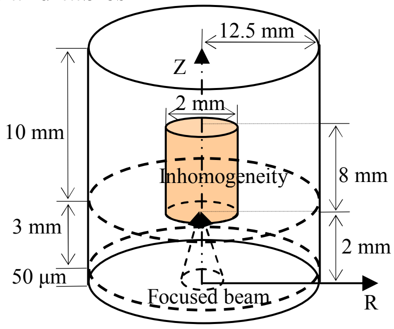

Fig.1 Tissue phantom model

Table 1 Optical properties of tissues

Layer	Thickness (mm)	Absorption Coef.(mm^{-1})	Scattering Coef. (mm^{-1})
Epidermis	0.05	0.355	0.824
Dermis	3	0.049	0.824
Fatty tissue	10	0.05	0.55
Inhomogeneity	8	0.051	1.228

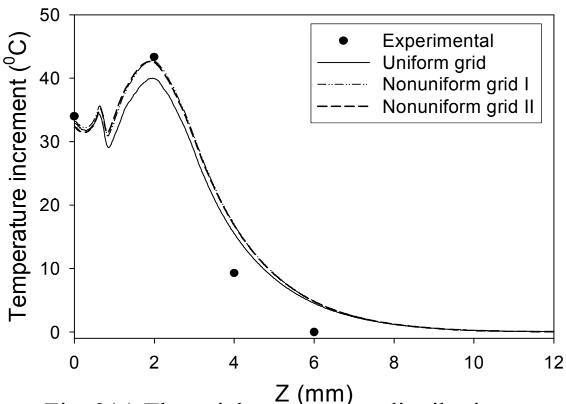

Fig. 2(a) The axial temperature distribution along the optical axis.

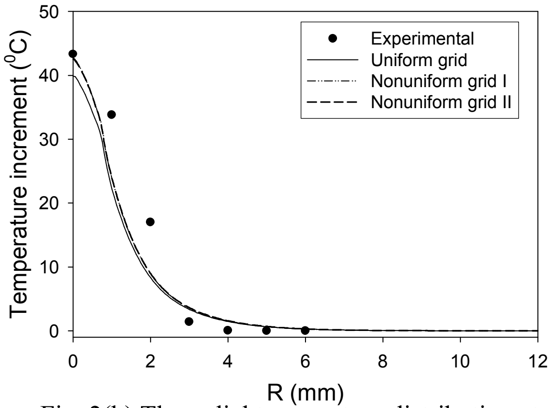

Fig. 2(b) The radial temperature distribution at Z = 2mm.

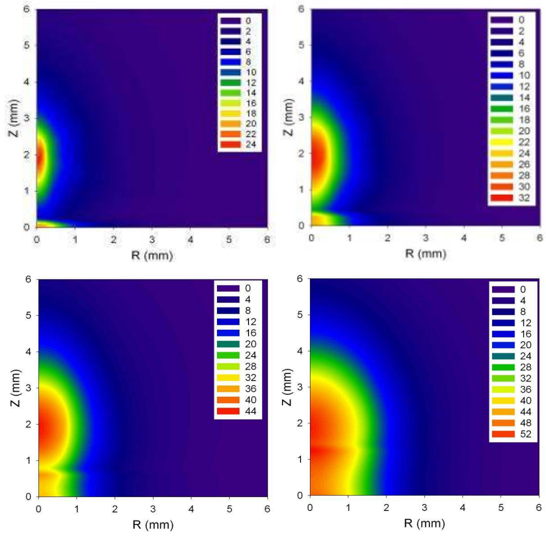

Fig. 3 The contours of temperature field at certain time instants: (a) t=2.5 sec, (b) t =5 sec, (c) t =10 sec, and (d) t = 20sec.

5. Conclusion

The prediction result of temperature distribution with the nonuniform grid system was well matched with the experimental one. The thermal wave motion was simulated and selective thermal damage took place in inhomogeneous region using focusing beam.

6. References

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