光 学 学 报
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Research of Heat Accumulation of Laser Irradiated Biological Cells

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Abstract Photo-thermal effect is one of the most important effects in the interactions between laser and biological tissue cells, however, its generation, transmission and action mechanisms are not yet clear. When laser irradiates biological cells, temperature is the decisive parameter in that temperature change in biological cells reflects a variety of physical properties of cells, which plays an important role in clinical applications. A numerical simulation model is built, and the heat accumulation process is simulated and analyzed using finite element software according to the heat transfer equations when laser irradiates biological cells. The temperature variation process of biological cells under different chopping cycles is analyzed, and equations of two temperature rise processes and two temperature drop processes are fitted when the chopper period is 0.1 s and the irradiation time is 0.2 s. It is concluded that the phenomenon of heat accumulation will appear only when the chopping frequency reaches a certain value; the highest temperature of thermal model which is irradiated by laser is related to the chopping frequency, and the higher the chopping frequency is, the lower the biological cell's thermal effect is.

Key words biotechnology; photo-thermal effect; heat accumulation; finite element software; chopping frequency

OCIS codes 170.1530; 140.3070; 170.3660; 170.1610

激光辐照生物细胞时热累积的研究

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摘要 光热效应是激光与生物组织相互作用时发生的重要效应之一，但其产生、传输和作用机理尚不十分清晰。激光辐照生物细胞时，温度是衡量其作用效果的重要参数，生物细胞中温度的变化间接反映了细胞的多种物理特性，在临床应用中有重要作用。建立了激光辐照生物细胞时的数值模拟模型，通过热传输方程，运用有限元软件模拟并分析了激光辐照生物细胞时的热累积现象。拟合并分析了不同斩波周期下生物细胞的温度变化过程，并拟合出斩波周期为 0.1 s、辐照时间为 0.2 s 时出现的两次温升、两次温降方程。实验结果表明只有当斩波频率达到一定值时才会出现热累积现象；同一激光辐照细胞热模型到达的最高温度与激光的斩波频率有关，激光斩波频率越高，所产生的光热效应越低。

关键词 生物光学；光热效应；热累积；有限元软件；斩波频率

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1 Introduction

Laser is widely used in most fields thanks to its characters of good monochromaticity, directivity and high brightness[1]. In a study of biomedicine, laser technology has been used in clinical medicine, e.g. laser interstitial thermal therapy (LITT), laser resection [2-3]. The basic idea of the application of laser in clinical medicine is that

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the laser irradiating biological cells chooses the appropriate wavelength and exposure time for the damaged tissues through the thermal interaction between laser and biological tissue cells, kills diseased tissue cells, and does not damage the surrounding normal cells[4-6]. However, present research on the interaction between laser and biological tissue cells cannot satisfy the needs of clinical medicine. The paper uses the finite element software[7-9] to simulate and research the interaction between laser and biological cells at different chopping frequency, and it comes to the conclusion that cell heat accumulation occurs when the chopping frequency reaches a certain value and the maximum temperature of cells is related to the chopper cycle.

2 Model establishment

The paper describes the transient temperature field when laser irradiates cells by solving the biological heat transfer basic equation, Pennes equation[10] as Eq. (1):

$$\rho C \frac{\partial T}{\partial t} = \nabla(k \nabla T) + \rho_b C_b W_b (T_{art} - T) + S , \tag{1}$$

where ρ is the cell density, C is the specific heat of cell, T is the cell temperature, k is the cell thermal conductivity, S is the laser source, ρ_b is the blood density, C_b is the blood specific heat, W_b is the blood perfusion rate, T_{art} is the arterial temperature, and t is the computation time.

The heat source expression about (r, z, t) on the condition of axisymmetric cylindrical coordinates when Gaussian beam irradiates biological cells vertically is as follows[11]:

$$S(r,z,t) = \mu_a (1-R) \varphi_0 \exp\left(-0.5 \frac{r^2}{w^2} - \mu_t z\right) \exp[-4 (t-\tau)^2 / \tau^2] , \tag{2}$$

where $w(z) = w_0 \exp(0.5 u_s z)$, w_0 is the beam diameter, μ_a is the cell absorption coefficient, R is the reflectance, $\varphi_0 = 2p/(\pi w_0^2)$ is the incident luminous flux density and p is the laser power, τ is the laser irradiation time, and t is the computation time.

In the simulation of our research, tables 1 and 2 list the cell model parameters of thermo-physical properties and optical properties.

Table 1 Cell model parameters of the thermo-physical properties

Material	Density /(kg/m^3)	Specific heat /[(J/(kg·℃)]	Thermal conductivity /(W/m·k)
Cell membrane	800	2200	0.168
Cell sap	1000	4200	0.6

Table 2 Cell model parameters of tissue optical properties

Material	Absorption coefficient /cm^{-1}	Scattering coefficient /cm^{-1}	Reflectivity
Cell membrane (980 nm)	4	38	0.041
Cell sap (980 nm)	0.330	0	0.002

In the research we assume that the cell is spherical, the thermal physical parameters of the biological cells are independent on temperature and the light irradiation is the heat source of cell heat transfer.

Fig. 1 is the three-dimensional numerical simulation model of a biological cell. Part I and part IV are the environment area out of the cell, red zone part Ⅱ is the spherical cell membrane, part Ⅲ is the environment area in the cell, and parts Ⅱ, Ⅲ and Ⅳ are the laser irradiated area.

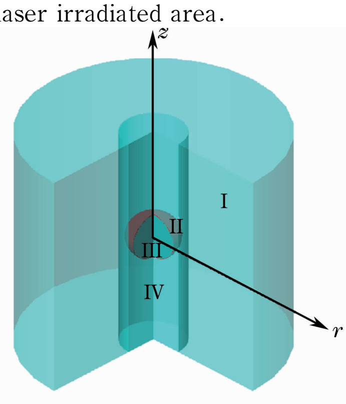

Fig. 1 Three-dimensional numerical simulation model of a cell

3　Simulation results and analysis

The heat transfer model of the biological cell was irradiated by the parallel beam whose chopper cycle lasts 1, 0.2, 0.1, 0.02 s, respectively and whose power is 72 mW.

Fig.2 is the temperature of the biological cell model as a function of time when the model was irradiated by laser whose chopper cycle is 1 s (Fig.2), half of the cycle (0.5 s) is for irradiation, the remaining 0.5 s is the cooling time. The mean of max in Fig.2 is the highest temperature of the whole cell at certain time when the laser irradiates the cell, and the min is the lowest temperature. The means of max and min are the same in Figs.5~8.

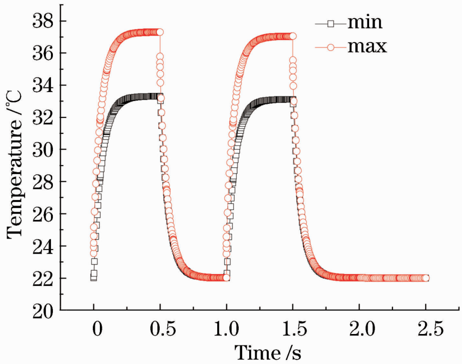

Fig.2　Temperature of the biological cell model as a function of time when the model was irradiated by laser with chopper cycle of 1 s

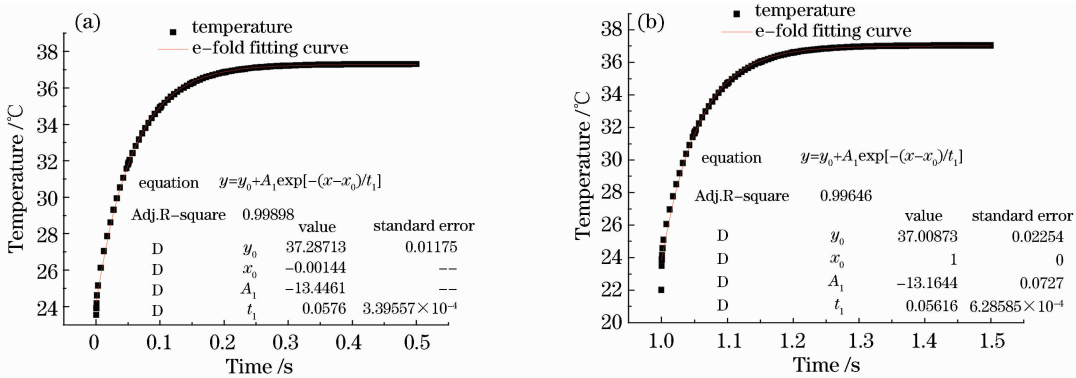

Fig.3　(a) Fitting curve of cell temperature rise in the period of 0~0.5 s; (b) fitting curve of cell temperature rise in the period of 1.0~1.5 s

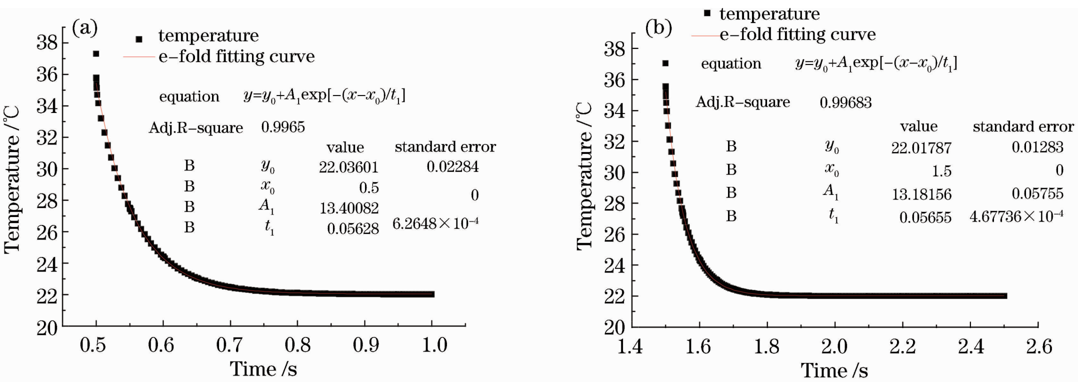

Fig.4　(a) Fitting curve of cell temperature drop in the period of 0.5~1.0 s; (b) fitting curve of cell temperature drop in the period of 1.5~2.5 s

For exponential fitting of the two temperature rise curves in the thermal process, the respective temperature rise equation fitting is as follows:

$$T(t) = 37.28 - 13.44\exp(-t/0.057), \tag{3}$$

$$T(t) = 37.008 - 13.164\exp[-(t-1)/0.056]. \tag{4}$$

The process of temperature rise and curve fitting in the two stages is shown in Figs.3(a) and 3(b) respectively.

Comparing the temperature rise curves and fitting equations of the two stages, it is found when the chopper cycle lasts 1 s, the two processes are similar: the time constant and exponential term are approximate and there is no thermal accumulation in the whole process. The process is equivalent to the superposition of two simple results of mono-pulse laser irradiating.

The two cooling equations through the index fitting of two cooling stages in Fig. 2 are as follows:

$$T(t) = 22.04 + 13.40\exp[-(t-0.5)/0.056], \tag{5}$$

$$T(t) = 22.01 + 13.18\exp[-(t-1.5)/0.056]. \tag{6}$$

The process of temperature drop and fitted curves in the two stages are shown in Figs. 4(a) and 4(b). Comparing the two cooling processes, the same conclusion as the temperature rise process is obtained: the two cooling processes are similar and their distinction is different time delay.

The thermal processes of the biological cell model which was irradiated by laser with different chopper cycles are shown in Figs. 5~7, and the chopper cycle is 0.2, 0.1 and 0.02 s respectively.

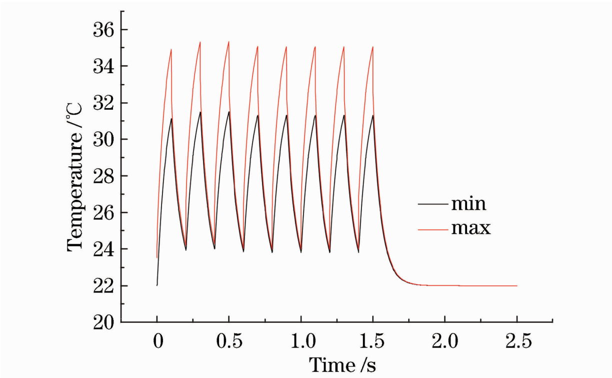

Fig. 5 Temperature of the biological cell model as a function of time when the model was irradiated by laser with chopper cycle of 0.2 s

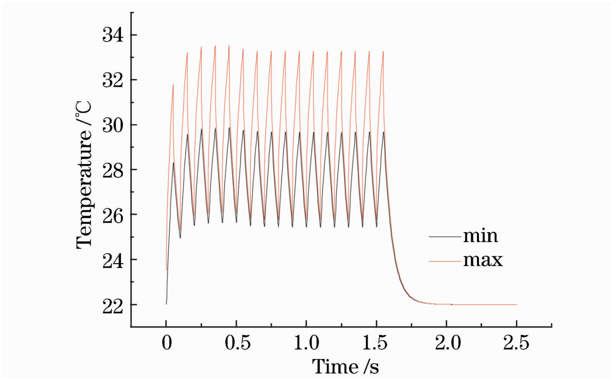

Fig. 6 Temperature of the biological cell model as a function of time when the model was irradiated by laser with chopper cycle of 0.1 s

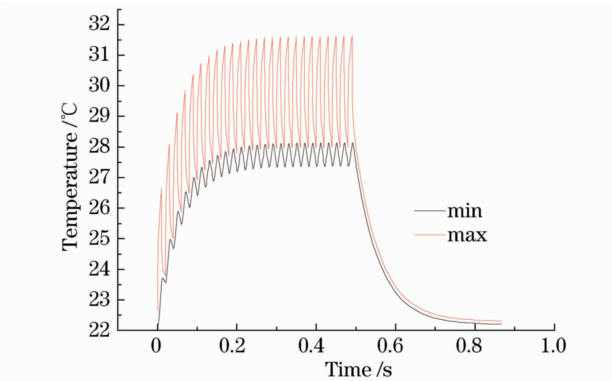

Fig. 7 Temperature of the biological cell model as a function of time when the model was irradiated by laser with chopper cycle of 0.02 s

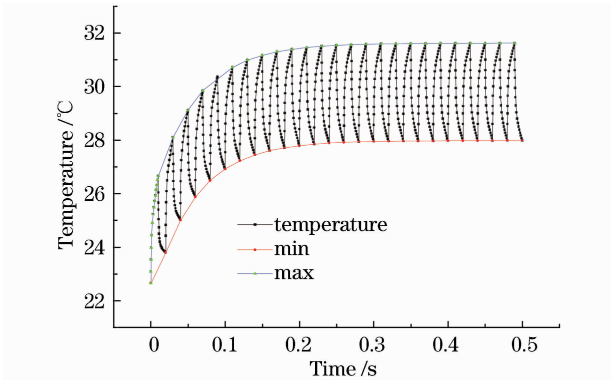

Fig. 8 Heat accumulation process of cells under pulse laser irradiation

Comparing the thermal diffusion process of the biological cell model in Fig. 2 and Figs. 5~7, it is observed that the heat accumulation emerges slowly with the decrease of chopper cycle. In other words, the initial temperature of the second pulse is higher than that of the first pulse. The process of temperature rise tends to be stable with the increase of pulse count, and the temperature turns stable with impulse hunting.

When the chopper cycle of laser is 0.02 s, the phenomenon of heat accumulation is obvious and increases with the form of index approximately, and then tends to be a stable temperature value. Fig. 8 is the heat accumulation process with the exponential fitting of the highest temperature of every pulse.

The temperature rise equation of each pulse at the highest temperature is

$$T(t) = 31.45 - 8.38\exp[-(t-0.0040/0.0316)]. \tag{7}$$

It is noted in the Fig. 8 that the lower the chopping frequency is, the more obvious the biological cell's thermal effect is.

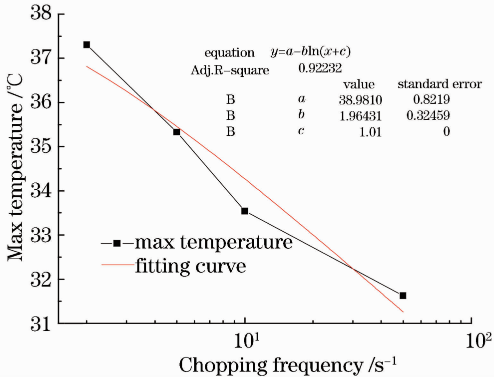

Fig. 9 Relationship between cell photo-thermal effect and chopping frequency under laser irradiation

4 Conclusion

Photo-thermal effect is one of the most important effects in the interactions between laser and biological tissue cells. The paper simulates and analyzes the biological cell model which was irradiated by laser, and the finite element software ANSYS workbench was used. It is concluded that the phenomenon of heat accumulation will occur only when the chopping frequency reaches a certain value; the highest temperature of thermal model which was irradiated by laser is related to the chopping frequency, and the higher the chopping frequency is, the lower the biological cell's thermal effect is.

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