Heat transfer characteristics of bio-materials irradiated by pulsed-laser*

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Abstract The dynamic temperature variation of bio-materials induced by pulsed-laser irradiation is determined by a rapid transient temperature measuring system. The heat transfer characteristics of bio-materials, and the influence of pulse duration, power density, thickness and initial moisture content of bio-materials on heat transfer are studied. Based on the experiments, a mathematical model of bioheat transfer is set up. Numerical simulation results show that the calculated results agree well with the experimental results, and bioheat transfer characteristics irradiated by pulsed-laser can be displayed well. Valuable information and experiences are provided for further experimental and theoretical investigation.

Keywords: **bio-materials, dynamic temperature measurement, pulsed-laser.**

Laser technology has been widely applied in the biological and medical engineering, such as laser surgery, laser mend and local heat treatment, laser diagnoses and sickness cures. The great advantages of laser medical application are shown increasingly, and surprising effects of laser as a substitute for traditional surgical operation have been found. Low power laser vascular irradiation can accelerate memory recovery, and improve brain tissue injured by the deficits of blood and oxygen. As a result, it significantly reduces the free radical's damage to the brain. Point irradiation by semiconductor laser can obviously improve the ability of immunity and recovery, enhance the resistance to freed gene, reduce the damage to organism or cell, rapidly lower blood viscosity, considerably decrease RBC press volume, accelerate blood circulation, and improve local blood supply and nutrition of organism[1~3]. All of these applications involve the thermal effects of laser irradiation tissue, for example, the high temperature caused by laser irradiation can directly destroy metastasis tissue by cauterizing and solidifying, laser can heal blood vessel and plexus after operation, and incise and separate tissue with high power.

No matter what medical application of laser is concerned, some fundamental problems will be faced, including the physical nature of interaction between laser and tissue, adaptability and the thermal reaction of normal and metastasis tissues toward laser, the laser parameter selection for various cures, tissue variation, temperature and energy control etc. The solving of these problems will help to ensure optimum medical results, and to protect health tissue from injuring. However, so far the theoretical understanding on laser application in biomedicine engineering is poor, and the optimum parameters selection mainly depends on the clinical experiences. It is necessary to determine qualitatively and quantitatively the interaction law between laser and tissue, to understand the mechanisms of light and thermal actions as well as thermal physics process of tissue, so as to provide credible foundation for medical application of laser. Therefore, the study on the bioheat transfer characteristics has great theoretical and practical significance.

1 Experimental rig and measuring principle

1.1 Experimental set-up

Fig. 1 is the schematic diagram of the experimental system. The heating source is a microsecond pulsed-laser (NdYAG). The wavelength is 1.06 μm, and the power density, pulse duration and spot diameter can be adjusted within the ranges of 1.0 ~ 10^4 MW/m^2, 1 ~ 30 μs and 1 ~ 10 mm, respectively. A platinum resistor (about 1 mm long, 0.2 mm wide and 1 μm thick) deposited on the top surface of a

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Φ1.6 mm quartz glass cylinder under vacuum condition, was used as the temperature sensor. Silver thread was used to connect the platinum resistor and the instrument for temperature measurement because it does not harm platinum and can be made very thin to improve the measurement precision. The response time to the temperature variation was less than 1 μs[4~6]. During the experiments, bio-materials were put on the top surface of platinum resistor, the diameter of laser spot is larger than that of the bio-materials which was in close contact with the platinum resistor, to ensure that the heat transfer is only in the longitudinal direction. Other facilities include a DL2700 digital oscilloscope (sampling rate is 500 MS/s) and a computer.

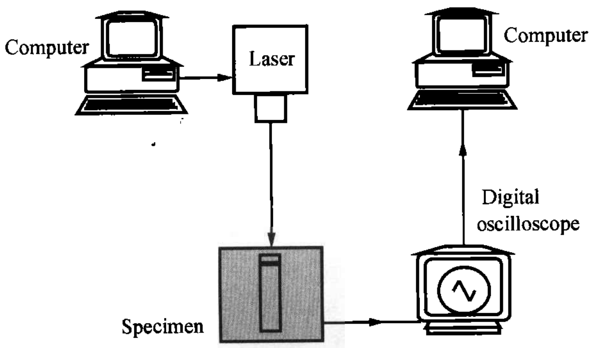

Fig. 1. Schematic diagram of experimental set-up.

1.2 Measuring principle

When the laser beam irradiates on the surface of sample (bio-materials), the laser acts with the sample and transfers to every layer of the sample, the temperature of the lower surface of the sample varies, which will result in the change of resistance of platinum resistor. The resistance signal is sent from the sensor to the signal converter, and is converted into voltage signal, then sent to the oscilloscope (sampling rate is 500 MS/s), which is used to record the signal.

1.3 Experimental process analysis

The interaction of laser with object is very complicated when a laser beam irradiates on the object. Usually the laser heating is treated as the non-source heat conduction with second type of boundary condition, where the interaction between laser beam and object only takes place at the surface, with only heat conduction inside the object. In fact, however, the absorption of laser energy by the object does not only take place at the surface of the object, especially for the bio-materials[7], which is also testified by our experiments. A part of energy is reflected, and the remained energy enters the interior of the object as laser beam irradiates the object, and the laser energy attenuates gradually because of the absorption and dispersion on the way. Dispersion makes the effect area of laser beam amplify many times after entering a heterogeneous object and the absorbed energy is transferred into thermal energy, making the temperature rise. The absorption of laser energy by object is volumetric absorption over certain cubage.

In this study, slices of mutton with the thickness of 1.2 mm ~ 5 mm were used as materials. A slice of mutton was put on and in close contact with the top surface of temperature sensor. When the laser beam irradiates on the surface of bio-materials, a part of energy is reflected, the other part enters bio-materials and is absorbed and scattered along its path. The energy attenuates according to certain law, and the remained energy will reach the top surface of sensor. Then a part of energy is reflected into the bio-materials from the top surface of sensor again and then is absorbed. As a result, the laser energy is reflected many times and is totally absorbed finally. The temperature of sensor surface is tested, which roughly reflects the temperature of the lower surface of bio-materials.

The temperature variation was measured for bio-materials of various thickness and initial moisture content induced by single pulsed-laser irradiation, and the influence of laser irradiation parameters (pulse duration, power density) was determined also.

2 Experimental observation

Fig. 2 shows the temperature variation of lower surface of the bio-material. It can be seen that the temperature rises rapidly to its maximum within the duration of laser pulse, then drops sharply after the end of laser irradiation, and levels off afterwards. The trend of temperature variation is almost the same for various conditions. If the interaction of laser and bio-materials only takes place at the surface, the lower surface could not feel such strong temperature variation in such a short time for the bio-materials with small thermal diffusion coefficient. This shows that the penetrating depth of pulse laser into bio-materials is large, and the heat transfer inside the bio-materials should include the effect of volumetric absorption. It can also be seen that pulse duration (t_p) has an important influence on the temperature variation, and the temperature increases with the increasing of pulse duration for the same thickness and power density. The higher the pulse duration, the longer the laser heating time; and the larger the total energy, the higher the temperature of bio-materials.

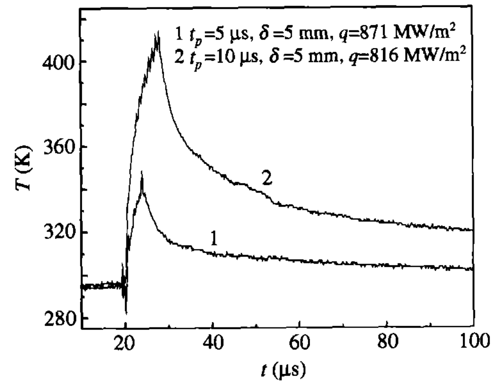

Fig. 2. Temperature variation at various pulse duration.

Fig. 3 presents the temperature variation of various power densities. As shown in Fig. 3, the temperature increases with the increase of power density for various thickness and pulse duration. The higher the power density, the more energy can be absorbed by the sensor and the higher the maximum temperature and its variation extent.

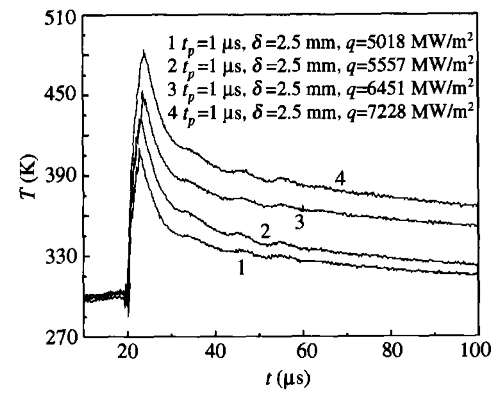

Fig. 3. Temperature variation for various power density.

In order to observe the temperature variation at various distances inside the bio-materials, the measurements for the bio-materials of different thickness were carried out. The results are shown in Fig. 4. The temperature decreases with the increasing thickness, i.e. the further from the heating disturbance, the more the energy attenuates and the less the temperature signal and its variation range.

Figs. 2 ~ 4 also show that when pulse duration and materials thickness are relatively small and the power density is considerably high, there is a fluctuation zone. After the ending of pulse laser, this phenomenon is weakened with the increase of pulse duration and materials thickness. The pulse duration and power density have a direct influence on the intensity of heat disturbance. When pulse duration is small, the transient intensity of heat disturbance is large; the larger the power density, the larger the transient intensity of heating disturbance; the thicker the materials, the more the energy attenuation, the less the energy reaches the surface of sensor. Therefore, there is a fluctuation range when the bio-materials are thin and transient intensity of heat disturbance is high, which cannot be described by the classical Fourier law. The real reasons of temperature fluctuation need to be further investigated in the future.

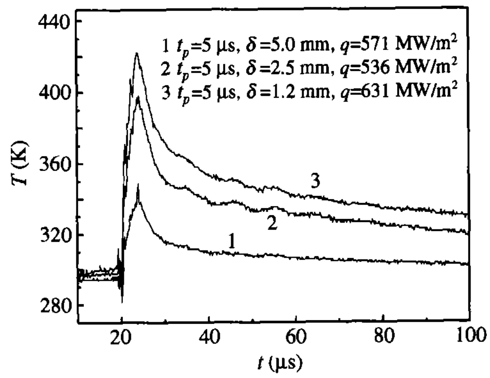

Fig. 4. Temperature variation for various thickness bio-materials.

Fig. 5 presents the temperature variation for different initial moisture content. The higher the initial moisture content, the lower the temperature, because more energy should be used to vaporize the water. The initial moisture content has some influence on quantitative results of temperature testing, but does not have any influence on qualitative results. Similar

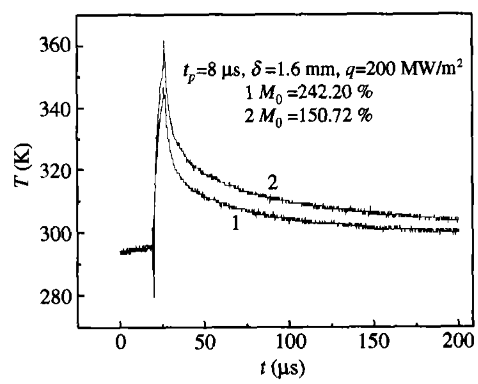

Fig. 5. Temperature variation for various initial moisture content of bio-materials.

results are also shown by other experiments.

Although the precision of temperature measurement needs to be improved, the above mentioned information might be provided for exploring the heat transfer characteristics of laser in bio-materials.

3 Theoretical analysis

In order to reveal the basic law of bioheat transfer, one dimension model shown in Fig. 6 was set up. Considering the fluctuation phenomena observed in the experiments, the following non-Fourier equation is used to describe the heat transfer:

$$q_m + \tau_{qm} \frac{\partial q_m}{\partial t} = -\lambda \frac{\partial T_m}{\partial x_m}, \quad (1)$$

$$\frac{\partial q_m}{\partial x_m} = Q_m(x, t) - (\rho C_p)_m \frac{\partial T_m}{\partial t_m}. \quad (2)$$

When $m = 1$, Eqs. (1) and (2) present the heat transfer of bio-materials; $m = 2$, Eqs. (1) and (2) present the heat transfer of temperature sensor,

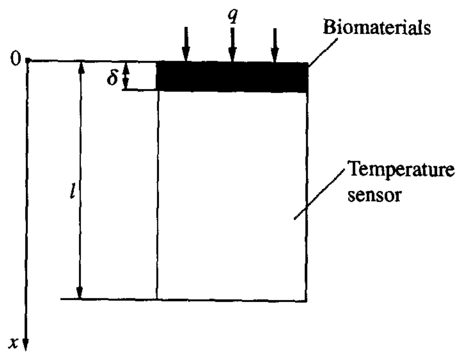

Fig. 6. Schematic diagram of simple model.

where q is the power density, λ heat conduction coefficient, T temperature, t time variable, τ_q heat relaxation time, ρ density, C_p specific heat, and Q heat source intensity.

When the laser energy q irradiates on the surface of bio-materials, a part of energy is reflected by the surface, the other part $q(1-r_1)$ enters the bio-materials and attenuates according to exponential law $e^{-x/d}$, the energy $q(1-r_1)\cdot r_2 \cdot e^{-\delta/d_2}$ that reaches the surface of sensor is reflected into the bio-materials again and finally is absorbed. The heating source intensity of bio-materials and sensor are derived respectively as the following.

$$Q_1(x_1, t) = \{q \cdot (1 - r_1) \cdot [e^{-x_1/d_1} - e^{-(x_1+dx_1)/d_1}] + q_b \cdot r_2[e^{-(\delta-x_1-dx_1)/d_1} - e^{-(\delta-x_1)/d_1}]\}/dx_1,$$

$$Q_2(x_2, t) = \{q_b \cdot (1 - r_2) \cdot [e^{-x_b/d_2} - e^{-(x_2-dx_2)/d_2}]\}/dx_2,$$

where r_1 and r_2 represent the reflectivity of bio-materials and sensor, d_1 and d_2 are the characteristic absorbing lengths of the bio-materials and the sensor for laser beam, respectively, δ is the thickness of bio-materials, q_b the laser intensity at the surface of bio-materials and sensor.

$$q_b = q \cdot (1 - r_1) \cdot e^{-\delta/d_1},$$

with the initial conditions:

$$t = 0, \quad T_m = T_{m0}, \quad \frac{\partial T_m}{\partial x_m} = 0,$$

and the boundary conditions:

$$t > 0, \quad x = 0, \quad q_1(0, t) = 0;$$
$$x = \delta, \quad q_2(0, t) = q_1(b, t),$$
$$T_2(0, t) = T_1(b, t);$$
$$x = l, \quad q_2(l, t) = 0.$$

As an initial exploring investigation, the heat transfer equations for sensor have been solved in this paper, i. e. only the energy that reaches the surface of sensor and is absorbed by this surface is taken into account. Fig. 7 shows the predicted and experimental temperature variations on the experimental condition given in Fig. 2. As shown in the figure, the calculated results agree well with the experimental data, and bioheat transfer characteristics can be reflected well. Theoretical analysis also shows that most of laser energy is absorbed along its path.

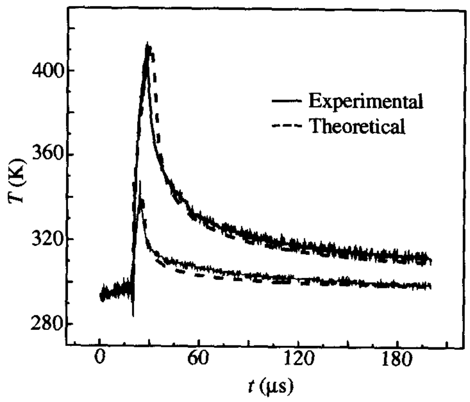

Fig. 7. Temperature variation with the time.

4 Conclusions

The following results have been obtained by experimental and theoretical analyses for bio-materials irradiated by pulsed- laser.

(i) The penetration and absorption of laser in bio-materials is considerable, the heat transfer inside the bio-materials should include the effect of volumetric absorption and cannot be treated as heat conduction without source.

(ii) Pulse duration, power density, and bio-materials thickness have significant influence on the temperature variation. The temperature increases with the increase of pulse duration and power density, and decreases with the increase of bio-materials thickness.

(iii) The higher the initial moisture content of bio-materials, the lower the temperature. The initial moisture content has an influence on the quantitative results of temperature testing.

(iv) The predicted results of the non-Fourier heat conduction model with heating source agree well with the experimental results, and it can reflect the basic heat transfer characteristics of bio-materials.

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