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Simulation of temperature distribution in skin under laser irradiation with different wavelengths

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ABSTRACT

With the help of numerical calculations of the finite element method, we simulate the distributions of the temperature in skin after laser irradiation with four wavelengths, 532 nm, 694 nm, 755 nm, and 800 nm, respectively. Combined metabolism of the organism with the traditional Pennes equation, the induced thermal effect in tissue is expressed. The simulated results show that the temperature in the irradiation center decreases as the increase of the wavelength for the same irradiation duration, and the relationships of the distribution of temperature and the wavelength along the radial and longitudinal directions are different.

1. Introduction

Laser is becoming more and more important in surgical and orthopedic applications. Compared with traditional methods, laser surgery is more effective and reliable with small wound and quick recovery. It is carried out by the penetration and light scattering in bio-tissue under laser radiation, which results in heating of comparatively larger volumes through the thermal conversion of the absorbed light energy.

The ideal effect of laser surgery is not only the total cauterization of diseased tissues but also the protection of healthy tissues from injuring. Therefore, reasonable laser parameters are very important, which directly influence the surgery effect. Small differences in any of these parameters may lead a disastrous application. Some priori knowledge about the effect of each parameter is necessary. Nowadays, the energy, pulse duration, and focus spot of laser have been used to investigate the thermal effect of laser–tissue interaction [1,2]. The temperature field in bio-tissue is determined by their thermal properties, the boundary and initial conditions, and heat loads. The first two factors are totally independent of laser wavelength. However, heat loads is completely determined by the optical absorption and scattering properties of bio-tissue. Further, their absorption coefficient (μ_a), scattering coefficient (μ_s), anisotropy factor (g), and the refractive index (n) are different with different light wavelengths.

It has been known that wavelengths used in laser surgery range from visible light to infrared light. Although thermal calculation by finite element method of multilayered skin under laser has been performed for more than 20 years, the temperature distributions in skin after laser irradiation with different wavelengths have not been discussed in detail. Based on the experimental results of Tseng [3] and the three-layer-skin structure model, we study the temperature distribution in skin by the numerical simulation method and get the relationship between the temperature field and laser wavelength.

2. Method

2.1. Heat conduction in skin

Given laser irradiation and the boundary conditions of air–skin interface, when Pennes heat transfer equation is used for *in vivo* skin, we can get the following expression:

$$\delta_{ts}\rho C\frac{\partial T}{\partial t}+\nabla\cdot(-k\nabla T)=\rho_b C_b\omega_b(T_b-T)+Q_{met}+Q_{ext}, \tag{1}$$

where, δ_{ts} is a time-scaling coefficient. ρ is the tissue density, C is the specific heat of tissue, k is the tissue's thermal conductivity. On the right side of the equation, $\rho_b C_b\omega_b(T_b-T)$ is a source term for the blood perfusion, where, ρ_b is the density of blood, C_b is the specific heat of blood, ω_b is the blood perfusion rate, and T_b is the arterial blood temperature. Q_{met} is the heat source from metabolism; Q_{ext} is the spatial heat source.

The boundary conditions can be set as the following:

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(1) The air–skin interface meets the conditions of the natural convection boundary. The environment temperature is 298 K.
(2) Other boundaries of the skin meet Dirichlet constant temperature conditions, which is equal to 309 K.

2.2. *Finite element analysis*

The finite element method (FEM) is a powerful tool in the solution of heat transfer for its strong boundary adaptability and controllable precision [4–8]. A multilayered finite element model to simulate the propagation of laser through skin can give us the comprehensive description and also provide an approximate solution to the heat conduction equation (1), which is solved between the individual nodes of a mesh using shape functions. The classical heat conduction equations for the finite element analysis with the heat capacity matrix $[C]$, the conductivity matrix $[K]$, the heat flux vector $\{P_1\}$ and the heat source vector $\{P_2\}$ can be expressed as

$$[K]\{T\} + [C]\{\dot{T}\} = \{P_1\} + \{P_2\}, \tag{2}$$

where, $\{T\}$ is the temperature vector, $\{\dot{T}\}$ is the temperature rate vector.

For the wave propagation, and ignoring damping, the governing finite element equations are

$$[M]\{\ddot{U}\} + [K]\{U\} = \{F_{ext}\}, \tag{3}$$

where $[M]$ is the mass matrix, $[K]$ is the stiffness matrix; $\{U\}$ is the displacement vector, $\{\ddot{U}\}$ is the acceleration vector, and $\{F_{ext}\}$ is the external force vector. For thermo-elasticity, the external force vector for an element is $\int_e [B]^T[D]\{\varepsilon_0\}\,dV$, where $\{\varepsilon_0\}$ is the thermal strain vector, $[B]^T$ is the transpose of the derivation of shape function, and $[D]$ is the material matrix.

3. Physical properties and structure of the investigated tissues

Although human skin is a complex heterogeneous medium, it is common to approximate skin as a three-dimensional half-infinite three-layered medium for simple description and calculation [9].

According to the actual clinical surgery, we selected four different wavelengths, 532 nm, 694 nm, 755 nm and 800 nm, and assuming the output of the laser is continuous. It is supposed that the laser spot is circular and the laser irradiates the skin perpendicularly, where heat source was confined. A two-dimensional skin model was constructed in an axial symmetry configuration with three different layers (epidermis, dermis and subcutaneous tissue). It was also given that the tissue is approximately uniform in the same layer, which means there is no difference in their thermal and optical parameters in the same layer.

We consider the skin type I–II in this paper and use their absorption and scattering coefficients of different wavelengths in epidermis of the upper inner arm from Ref. [3]. For all these lasers, the absorption coefficients of dermis and subcutaneous tissue are set as 0.7 (/cm) and 1.0 (/cm), respectively; the scattering coefficients are set as 180 (/cm) and 50 (/cm), respectively [10].

According to Refs. [10,11], other main parameters of each layer of skin used in our simulation are shown in Table 1. In addition, moisture content of blood is about 80%. Density of blood ρ_b is 1.06 g/cm^3. Specific heat of blood C_b is 3.66 J/(g K). Arterial blood temperature is 309.5 K. R (the reflectivity of the skin) is 0.35. The numerical simulation's initial value T is 309 K ($t = 0$). Laser power P is set as 2 W, the waist w_0 is 0.05 cm. The calculated region r^*z is 1*1.2 cm^2.

Table 1
Main parameters of each layer of skin [10,11].

	Epidermis	Dermis	Subcutaneous tissue
Thickness (mm)	0.05	1.95	10
Tissue density ρ (g/cm^3)	1.2	1.09	1.21
Specific heat of tissue	3.95	3.35	2.24
Thermal conductivity k (mW/(cm K))	2.4	4.2	1.94
Blood perfusion Wb (g/(cm^3 K)	0	1.25	1.25

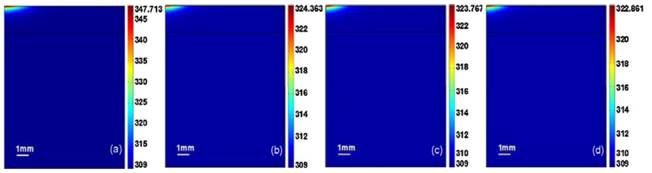

Fig. 1. The temperature field in skin after laser irradiation with four different wavelengths, where irradiation duration is 10 s. (a)–(d) correspond to those of the wavelength 532 nm, 694 nm, 755 nm and 800 nm, respectively. Axisymmetric cylindrical coordinates are used in our simulation, so only half of the section is shown in all of the figures.

4. Results and discussion

In this paper, we mainly investigate the distribution of the temperature of skin in two aspects, one is under the same irradiation duration and the other is the same highest temperature in the irradiation center.

The simulated results of the same irradiation duration ($\tau = 10$ s) are shown in Figs. 1 and 2. Fig. 1 shows the overall temperature field. When laser focuses on the surface of skin, light transmits into the epidermis firstly and causes great attenuation. From Fig. 1, we can see that the temperature in the irradiation center is the highest and the temperature of the tissue diffuses from the irradiated region to the surrounding tissue for all wavelengths after laser irradiates. However, the high temperature area decreases with the increase of the wavelength and the temperature in the irradiation center decreases as the increase of the wavelength.

In order to see the distribution of the temperature clearly, the temperature along the radial at the surface ($z = 0$) and the longitudinal direction ($r = 0$) at 10 s are shown in Fig. 2(a) and (b), respectively. From Fig. 2, we can see that laser with 532 nm wavelength has the highest center temperature and the largest area for the same temperature. Skin absorbs more energy for 532 nm than other three wavelengths and converts it into heat. In Fig. 2(b), axial temperature distribution reflects the heat distribution in different layers in skin. It can be seen that the change of the temperature field mainly concentrate on the epidermis and the dermis, and the temperature gradient of the epidermis is greater than that of the dermis. That is because the optical properties and thermal parameters of skin of each layer are much different. Comparing Fig. 2(a)

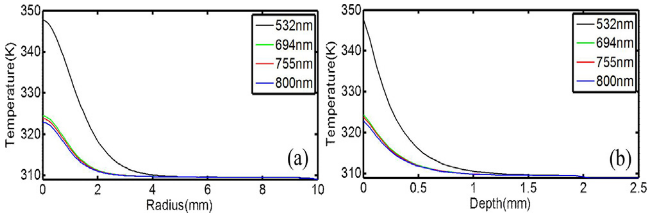

Fig. 2. The distributions of the temperature along the radial (a) and the longitudinal direction (b) when the duration is 10 s. Black, green, red, and blue curves represent the results of laser of 532 nm, 694 nm, 755 nm, and 800 nm, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)