Simulated Distribution Characteristics of Surface Temperature on Irradiating of a Laser

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ABSTRACT

In this paper, we concern about the distribution characteristics of surface temperature by the increment of time, diffusivity and heat flux on irradiating of a laser. The penetration depth corresponding to the induced constant heat flux or irradiated laser, is simulated by a computer algorithm. The distribution of temperature versus penetration depth for the variation of time and diffusivity is characterized at the constant heat flux and on irradiating of a laser. The temperature of constant heat flux at the fixed diffusivity or time, is decreased by the pattern of exponential function as the time t or diffusivity α is increased (α=10, 100, 1000). The temperature of constant heat flux is not changed but exponentially fixed with the increasing diffusivity and the fixed time. On the other hand, the temperature of laser at the fixed diffusivity or time is decreased linearly. Our results show that the characteristics of the simulated surface temperature in a semi-infinite solid are similar to the graphs on theoretical consideration.

Keywords: *Surface Temperature, Computer Algorithm, Laser Irradiation, Constant Heat Flux, Penetration Depth*

1. INTRODUCTION

The propagation of light like as ultraviolet, visible and infrared in tissue has been to many diagnostic and therapeutic applications for photobiology and photomedicine. In the recent years the medical applications of laser have aroused great interest in the interaction of optical properties in the irradiated biological tissue. The clinical use of a laser is typically based on a compromise of four considerations such as laser-tissue interaction mechanisms, the penetration depth of laser irradiation on tissue, the availability of the laser and the availability of optical fibers to transmit a wavelength on the desired tissue. There are many clinical trials of cancer or benign cells, dermatology, gastroenterology, ophthalmology, pulmonary disease, laser angioplasty, tissue welding, neurology, plastic surgery, etc[1]. The laser light depends upon the optical properties of the tissue at the wavelength of the selected laser.
The distribution of laser light is important and is determined essentially by the interaction with the optical properties and heat transfer. Most tissues are inhomogeneous turbid media in which the irradiated laser light may be complex. Figure1 shows the schematic distribution of estimated tissue penetration depth of various commercial lasers as a function of wavelength.

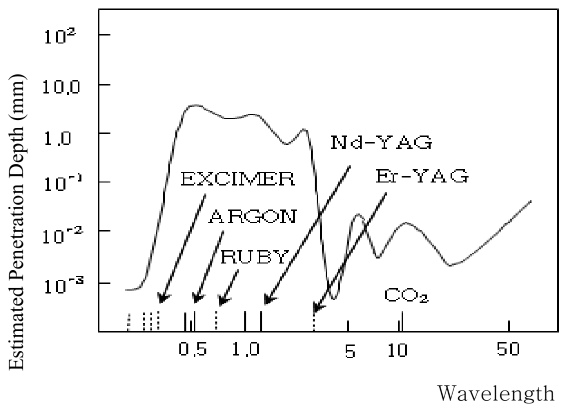

Fig. 1 Estimated tissue penetration depth as a function of wavelength

Dashed lines indicate pulsed lasers and other lasers produce laser light continuously. Among the current lasers on the horizontal axis, the dashed lines indicate the pulsed lasers of Er-YAG, Ruby and Excimer laser. The solid lines indicate the continuous wave lasers of Argon, Nd-YAG and CO_2[2].
Models of various complexity have been used to predict the distribution characteristics of the temperature in the tissue with the optical effects such as scattering, absorption, heat transfer, etc[3]-[5]. A lot of models based on the heat conduction equation have been developed to compute the increased temperature and damage status of tissue by the irradiated laser. The thermal response during laser irradiation is highly dependent upon the optical properties of the corresponding media, for example, the biological tissue[6], [7]. In addition, the temperature characteristics with both of the penetration

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depth and the induced time are computed for the constant heat flux problem and a laser problem in a semi-infinite slab. In this paper, constant surface temperature and constant surface flux problems by computer simulation are considered in a semi-infinite solid and the associated solutions to the corresponding equations are proposed for medical treatments.

2. COMPARISON OF CONSTANT SURFACE TEMPERATURE WITH CONSTANT HEAT FLUX

2.1 Constant Surface Temperature

Assume that the interesting surface is maintained at a fixed or constant temperature in the surface (Ts). At some initial time, the situation is time dependent. In that case, two boundary conditions are needed because of the heat equation in the spatial coordinate. Also the only one initial condition is specified (at z=0) because the equation in time is the first order. The heat transfer is in the positive direction of depth with the temperature distribution (T(z, t)) as a function of position and time. In case of the semi-infinite solid, if there is any sudden change of conditions which is imposed at this surface, then transient conduction will occur within the solid and one-dimensional conduction will occur. The transient temperature distributions in a semi-infinite solid and the associated solutions to equations are as follows.

By Dirichlet's boundary condition,

T (0, t) = To

$$\frac{T(z,t) - Ts}{To - Ts} = \mathrm{erf}\left(\frac{z}{2\sqrt{\alpha t}}\right) \quad (1)$$

$$q_s(t) = -k\left.\frac{\partial T}{\partial z}\right|_{z=0} = \frac{k(Ts - To)}{\sqrt{\pi \alpha t}} \quad (2)$$

The variables from the expression (1) and (2) are respectively, the temperature T(z,t)(^{o}K) as a function of penetration depth z(mm) and time t(sec), the initial temperature To(^{o}K) at time t=0, an interesting surface temperature Ts(^{o}K), a penetration depth z, the heat flux $q_s(t)$ as a function of time t in the surface, a diffusivity α(cm^2/s), an error function erf ( ) and a heat conductivity k(joule/cm·s·°c).

As you can see on the graph (Fig.2), the error function is zero at z=0 (depth), T(0, t) = Ts and T(∞, t) = To. However, when time t is increased, transient temperature is increased with decreasing. When the depth z is increased, the temperature is decreased.

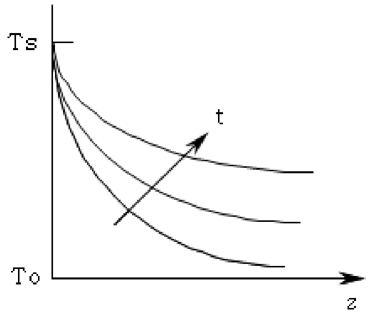

Fig.2 Transient temperature distribution in a semi-infinite solid in case of constant surface temperature

2.2 Constant Heat Flux

At some initial time, the situation is the time dependent. Assume that surface is maintained at a fixed or constant heat flux in the surface (q_s). Two boundary conditions are needed by the second order of the heat flux equation and the equation in time is the first order. The heat transfer has the temperature distribution (T(z, t)) as a function of position and time like as in the constant surface. In case of finite flux for insulated surface, the equation is able to express by the equation (3).

$$\left.\frac{\partial T}{\partial z}\right|_{z=0} = 0 \quad (3)$$

For the early portion of the transient, the temperature in the slab interior is uninfluenced by the change in surface conditions. The transient temperature distributions in a semi-infinite solid and the associated solutions to equations are as follows.

By Neumann's boundary condition,

$q(0, t) = q_s$

$$T(z,t) - To = \frac{2q_s(\alpha t/\pi)^{1/2}}{k}\exp\left(\frac{-z^2}{4\alpha t}\right) - \frac{q_s z}{k}\,\mathrm{erfc}\left(\frac{z}{2\sqrt{\alpha t}}\right) \quad (4)$$

Here the variables introduced are the heat flux q_s in the surface, the diffusivity α of constant heat flux, a thermal conductivity k(W/k·m) and the volumetric heat temperature ρc(J/cm^3·k).

As you can see on the graph of figure 3, the initial value To at z=0 has different values. Also as the depth z is increased, the transient temperature is decreased. But as the time is increased, the temperature is increased. This heat flux is related to the temperature gradient at the surface by Fourier's law as following expression (5).

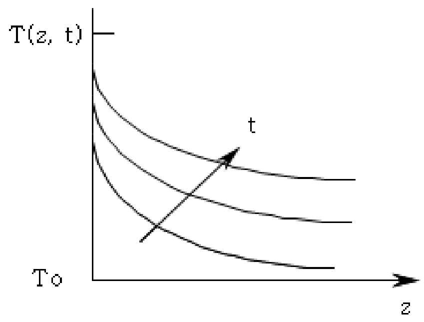

Fig.3 Transient temperature distribution in a semi-infinite solid in case of constant heat flux

$$q_s(t) = -k \left.\frac{\partial T}{\partial z}\right|_{z=0} \quad (5)$$

3. RESULTS AND DISCUSSION

The simulated results of temperature for applications of a constant heat flux and a laser are graphed as follows (Fig 4(a), (b), (c) and (d)). The transient temperature of constant heat flux at a given depth is increased as the time t is increased (Fig.4(a)). Also, the temperature at the given time t when α is increased (α = 10, 100, 1000), the values are not changed (Fig.4(c)) but such values of laser are increased with decreasing linearly with small values in this case (Fig.4(d)).

Generally the temperature by laser in this case, is very low comparing with that of constant heat flux (Fig.4(b) and (c)). Fig.4(b) shows that the temperature is linearly fixed as the time is increased with the fixed diffusivity. The temperature of constant heat flux is decreased by similar pattern of exponential function (Fig.4(a)) but that of laser is decreased linearly with very small change (Fig.4(d)). The associated formulas for computation by a program are as follows :

i) The temperature (T_H) by constant heat flux:

$$T(z,\ t) = To + \frac{2q_s(\alpha t/\pi)^{1/2}}{k}\ \exp\left(\frac{-z^2}{4\alpha t}\right) - \frac{q_s z}{k}\ \mathrm{erfc}\left(\frac{z}{2\sqrt{\alpha t}}\right) \quad (6)$$

where q_s = Io, $\alpha_H = k/\rho c$. Io is a surface radiance(W/cm^2) and α_H is the diffusivity of constant heat flux.

ii) The temperature (T_L) by laser:

T(z, t) = To + θ (T_{ab} –To) where α_L = 10, 100 and 1000 with the time t = 0.1, 0.5 and 1.0 sec. The variables introduced are respectively the temperature T(z, t) as a function of penetration depth z(mm) and time(t), the initial temperature To at time t=0 sec, a dimensionless temperature θ and the critical ablation temperature Tab (K).

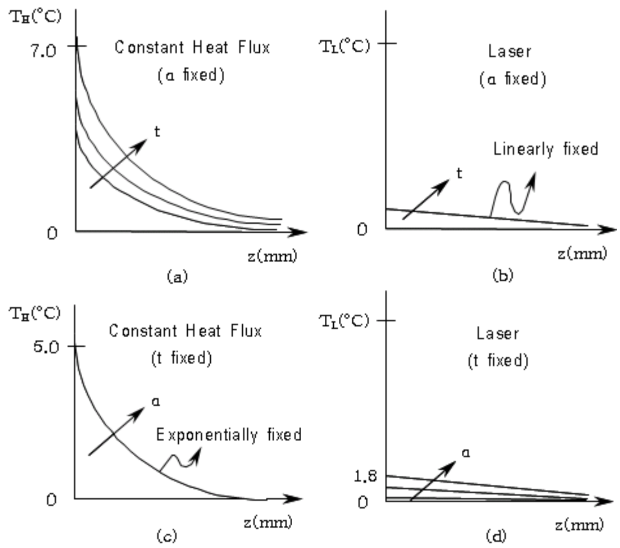

Fig.4 Simulated temperature for applications of a constant heat flux and a laser

4. CONCLUSIONS

The temperature T(z, t) and the penetration depth(z) with varying time and diffusivity in a semi-infinite slab are computed by program and showed by graphs in case of a constant heat flux and of a laser. The result shows that the distribution characteristics of simulated temperature provide the possibility of laser treatment.

From the result of computer simulation, the temperature with varying time at the constant heat flux and the fixed diffusivity is decreased exponentially with the different temperature at first, but increased a little with increasing time (Fig. 4(a)). The temperature with varying diffusivity at the constant heat flux and the fixed time is decreased exponentially but that is not changed as the diffusivity is increased. The penetration depth is generally increased. Therefore in case of constant heat flux, the temperature is generally decreased exponentially as the time and the diffusivity is increased and increased a little but is not related with increasing of diffusivity.

On the other hand, in case of a laser, the temperature at the fixed diffusivity is linearly decreased without change as the time is increased. But the temperature by irradiation of a laser is increased a little as the diffusivity is increased. The penetration depth is generally increased like that in case of the constant heat flux. Therefore in case of laser, the temperature is not changed by increasing of time but is linearly increased a little by increasing of diffusivity.

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