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A Thermal Model of Laser Absorption

Dustin G. Mixon and William P. Roach[*]

Air Force Research Laboratory, Human Effectiveness Directorate, Directed Energy Bioeffects Division, Radiofrequency Radiation Branch, Brooks City-Base, TX 78235

ABSTRACT

We give a closed-form expression for the temperature change induced by exposure to a continuous wave Gaussian laser under the assumption that no heat transfer occurs in the biological tissue. An explicit dependence of temperature change on fluence is established.

Keywords: thermal model, non-ionizing, radio frequency, laser, microwave

1. INTRODUCTION

The primary measure of laser absorption is the resulting change in temperature. Currently, models that calculate the thermal response of tissue to laser sources tend to employ numerical methods, which employ either the power density ($W \cdot m^{-3}$) or specific absorption rate (SAR) ($W \cdot kg^{-1}$) information of the tissue. The Takata thermal model[1] is usually evoked to predict the tissue's thermal damage from temperature change, which relies upon the Pennes bioheat equation[3]. Green's formalism[4] is used to solve this nonhomogeneous partial differential equation, and the solution tends to accurately depict the temperature rise in tissue.

Considering its applicability, a closed-form source term for the Pennes bioheat equation is desired. It is natural to employ the far field assumption for Gaussian-distributed laser beams (TEM00). This leads to a plane wave expression, given by applying both a spherical wave approximation and the Helmholtz formalism, while maintaining a classical characterization of the wave vector in terms of the material properties of the media of propagation[5-10].

In sum, we are interested in describing the change in tissue temperature that is induced by a Gaussian laser beam. This paper will limit its scope to the continuous wave case. Assuming no conductive or convective heat transfer effects exist within the tissue, we will first give the specific temperature change that that is induced by the Gaussian laser beam.

2. SPECIFIC TEMPERATURE CHANGE

Tissue temperature is commonly modeled according to the Pennes bioheat equation[3],

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T) - \rho_b C_b j (T - T_a) + q_h + P_d.$$

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[*] W.P.R.: E-mail: william.roach@brooks.af.mil, Telephone: 1 210 536 2770
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Here, ρ (kg·m^{-3}) and C (J·kg^{-1}·K^{-1}) are the density and heat capacity of the tissue, respectively, and ρ_b and C_b are the same values for blood. Further, T_a (K) is the temperature of blood in large arteries and j (s^{-1}) is the blood flow rate, that is, the rate at which a volume of blood traverses a volume of tissue over time. Finally, κ (W·m^{-1}·K^{-1}) is the tissue thermal conductivity, q_h (W·m^{-3}) denotes the heating due to metabolic processes, and P_d (W·m^{-3}) similarly denotes heating due to external processes, in this case, laser exposure.

Solving this partial differential equation for the specific temperature function can be quite arduous, and so the common modeling technique is that of computer-based discretization. In this work, however, we will attempt to find a closed-form expression for tissue temperature. In doing so, we will assume that conductive and convective heat transfers, as well as metabolic heating, are negligible. This leaves the expression of temperature in terms of the power density induced by irradiating the tissue:

$$\rho C \frac{\partial T}{\partial t} = P_d.$$

2.1 Power Density Induced by Delivered Intensity

Let us consider laser radiation with planer wave fronts. Further, suppose the radiation's direction of propagation is orthogonal to a half-space of semi-infinite homogeneous material. We will now determine the power density of interest in terms of the emitted intensity.

We define a cylindrical coordinate system according to our half-space. In particular, z (m) represents depth into the material, so that $z=0$ at the surface and $z>0$ inside the material. Further, r (m) represents the transverse distance, that is, the distance from the beam axis. Let $I(r)$ denote the specific intensity of laser at r meters from the beam axis. Then Beer's Law gives the specific power density in terms of the material's absorption coefficient α (m^{-1}):

$$P_d(r, z) = \alpha I(r)e^{-\alpha z}.$$

2.2 Top-Hat and Gaussian Intensity Profiles

Section 2.1 gives us the relation between the delivered intensity, which is assumed symmetric about the beam axis, and the power density. One such intensity profile, called the top-hat profile, is particularly useful in certain computer modeling applications. In this profile, the delivered power is uniformly distributed on a disk centered at the beam axis with some radius R. We therefore have the delivered intensity, written in terms of the total power emitted P (W),

$$I(r) = \begin{cases} \dfrac{P}{\pi R^2} & \text{for } r \leq R \\ 0 & \text{for } r > R \end{cases}.$$

Let us now consider a more natural intensity profile, Gaussian. We assume that the penetration depth into the material is significantly less than the Rayleigh range. With this assumption, Saleh and Teich[10] model the emitted intensity of a Gaussian beam by

$$I(r) = \frac{2P}{\pi w^2} e^{-2r^2/w^2},$$

where P is the total power emitted and w is the waist radius.

2.3 On Fluence

We submit the following practical definition of fluence; the *effective* fluence of the radiation is given, in terms of the total energy emitted E, by

$$\Phi = \frac{E}{\pi w^2}.$$

This definition does not imply that all of the energy is deposited within one waist radius of the beam axis. In fact, considering the Gaussian distribution of fluence, only 86% of the energy is found in this region. Rather, our definition is merely a practical scalar measurement of fluence for the application in the field of dosimetry, though we will find it particularly significant in the following section.

2.4 Specific Temperature Change and Fluence

We gave an expression for Gaussian intensity in Secton 2.2. Substituting this expression into the result from Section 2.1 yields a closed-form expression for the power density induced by laser radiation,

$$P_d(r, z) = \frac{2\alpha P}{\pi w^2} e^{-2r^2/w^2 - \alpha z}.$$

Assuming no conductive or convective heat transfer, we have the following expression for specific temperature change:

$$\Delta T(r, z) = \frac{2\alpha}{\rho C} \frac{E}{\pi w^2} e^{-2r^2/w^2 - \alpha z} = \frac{2\alpha \Phi}{\rho C} e^{-2r^2/w^2 - \alpha z}.$$

This gives the direct relationship between the effective fluence of the laser radiation and the resultant temperature change in the material.

3. CONCLUSIONS AND FURTHER RESEARCH

This paper has provided a derivation for the temperature change induced by exposure to a continuous wave Gaussian laser. It is important to note the assumption of no heat transfer effects throughout the material. In review, our expression for temperature is significant not only for its closed form, but also for its explicit linearity in the intensive quantity we defined as effective fluence.

Due to its lack of applicability, the "no heat transfer" assumption is quite cumbersome. However, with the source term of the Pennes bioheat equation now identified for our problem, finding a closed-form solution to this partial differential equation becomes a reasonable subject of further research. Also interesting is the biological response to a rise in temperature, and its

effect on the parameters found in the Pennes bioheat equation. Thirdly, the real-world prevalence of time-dependent power, that is, pulsed radiation, demands its consideration for modeling in the future.

REFERENCES

1. Takata, A.N., L. Zaneveld, W. Richter. Laser-Induced Thermal Damage of Skin. USAF School of Aerospace Medicine, Report SAM-TR-77-38, Brooks AFB, TX.
2. Yee, K.S. Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media. IEEE Transactions Antennas and Propagation, 14:302-307, 1966.
3. Pennes, H.H. Analysis of tissue and arterial blood temperatures in the resting human forearm. I. Apple. Phys., 1, 93, 1948, pp.93-122.
4. Welch, A.J., and M.J.C. van Gemert. Optical-Thermal Response of laser-Irradiated Tissue. Lasers, Photonics, and Electro-Optics. Plenum Press, New York, first edition, 1995.
5. Marshall, W.J., R.C. Aldrich and S.A. Zimmerman. Laser hazard evaluation method for middle infrared laser systems. J. Laser Appl. 8(4) pp. 211-216, 1996.
6. Neimz, M.H. Laser-Tissue Interactions: Fundamentals and Applications. Springer-Verlag, New York, 2004.
7. Reitz, J.R., F.J. Milford and R.W. Christy. Foundations of Electromagnetic Theory. Addison-Wesley, third edition, New York, 1980.
8. Jackson, J.D. classical Electrodynamics. John Wiley, second edition, New York, 1975.
9. Milloni, P. and J. Eberly. J. Lasers, Wiley, 1988.
10. Saleh, B.E.A. and M.C. Teich. Fundamentals of Photonics, John Wiley, New York, 1991, p.83.