

Chapter 1

Overview of Optical and Thermal Laser-Tissue Interaction and Nomenclature

Ashley J. Welch and Martin J.C. van Gemert

1.1 Introduction

The development of a unified theory for the optical and thermal response of tissue to laser radiation is no longer in its infancy, though it is still not fully developed. This book describes our current understanding of the physical events that can occur when light interacts with tissue, particularly the sequence of formulations that estimate the optical and thermal responses of tissue to laser radiation. This overview is followed by an important chapter that describes the basic interactions of light with tissue. Part I considers basic tissue optics. Tissue is treated as an absorbing and scattering medium and methods are presented for calculating and measuring light propagation, including polarized light. Also, methods for estimating tissue optical properties from measurements of reflection and transmission are discussed. Part II concerns the thermal response of tissue owing to absorbed light, and rate reactions are presented for predicting the extent of laser induced thermal damage. Methods for measuring temperature, thermal properties, rate constants, pulsed ablation and laser tissue interactions are detailed. Part III is devoted to examples that use the theory presented in Parts I and II to analyze various medical applications of lasers. Discussions of Optical Coherence Tomography (OCT), forensic optics, and light stimulation of nerves are also included.

Since the optical and thermal responses of tissue to laser irradiation are highly dependent upon the characteristics of the laser source, we will describe various laser parameters and their influence upon the tissue response. Basic irradiation parameters for any laser therapeutic procedure are (1) power, irradiation time, and spot size for continuous wave (*cw*) lasers, and (2) energy per pulse, irradiation time, spot size, repetition rate and number of pulses for pulse lasers. Perhaps the most important *cw* irradiation parameter is irradiance [W/m^2]. The irradiance is a function of the power delivered and the laser spot size on the tissue. Low irradiances that do not significantly increase tissue temperature are associated with diagnostic applications

A.J. Welch (✉)

Department of Biomedical Engineering, The University of Texas, Austin, TX, USA
e-mail: welch@mail.utexas.edu

such as OCT, photochemical processes and biostimulation, whereas high irradiances can ablate tissue, induce plasma formation, and create mechanical damage in tissue. The depth that laser light penetrates tissue depends upon the optical properties of tissue which vary with wavelength.

The spectrum of commercially available lasers for diagnostic and therapeutic medical applications stretches from 193 nm to 10.6 μm . Both *cw* and pulse lasers are available in the UV, visible and IR. Since the absorption and scattering of any tissue varies with wavelength, there are dramatic differences in the penetration depth of the radiation from the various lasers. Light at either 193 nm or 2.96 μm is totally absorbed in the first few μm of tissue owing to amino acid absorption in the UV and water absorption in the IR. In contrast, collimated light from 600 nm to 1.2 μm can penetrate several millimeters in tissue and the associated scattered light several cm. Within this red and near IR wavelength window there is a lack of strongly absorbing tissue chromophores. As the collimated beam passes through tissue, it is exponentially attenuated by absorption and scattering. The scattered light forms a diffuse volume around the collimated beam. Heat is generated wherever collimated or diffuse light is absorbed.

This book provides a detailed description of the optical and thermal response of tissue to laser radiation. We examine many of the physical events that are involved in the response of tissue to laser irradiation. Particular emphasis is placed on events that provide some insight into the optical response during treatment procedures or diagnostic applications of laser light.

These events are schematically depicted in Fig. 1.1 and they comprise a simplified optical, thermal and damage model for laser-tissue interaction. In this diagram, we introduce the natural sequence of laser induced events and the governing equations that will be used throughout the book. Modifications, boundary conditions, and solutions of these equations are given in the following chapters.

In Fig. 1.1, we assume that a laser beam with irradiance profile $E(x,y)$ strikes the tissue. The collimated beam in the z direction attenuates exponentially with tissue depth; light scattered from the collimated beam becomes the source for the resulting diffuse (scattered) light in the tissue. Propagation of the scattered light is described by the transport equation [1] (see Chapter 3) which examines the change in radiance with distance in direction \hat{s} at a position $\mathbf{r} = x, y, z$. Light (radiance) in direction \hat{s} decreases owing to absorption and scattering (first term on right side of transport equation in Fig. 1.1) and increases due to light that is scattered from other directions \hat{s}' into direction \hat{s} (second term on right side). The total fluence rate, $\phi(\mathbf{r})$, is the integration of radiance $L(\mathbf{r}, \hat{s})$ over all directions in space (over 4π steradians). In this book we separate radiance into its two components: scattered light $L_s(\mathbf{r}, \hat{s})$ and collimated (primary) light $L_p(\mathbf{r}, \hat{s}_0)$ (see Chapters 3 and 6).

Most of the light (collimated or diffuse) that is absorbed is converted to heat. Exceptions are light that produces photochemical reactions or photons absorbed by fluorophores that produce fluorescence. Typically, the light energy associated with these reactions is very small relative to the energy that produces thermal reactions. The rate of volumetric heat production $S(\mathbf{r})$ is the product of the total fluence rate at \mathbf{r} (collimated and diffuse parts) and the absorption coefficient at \mathbf{r} , $\mu_a(\mathbf{r})$.

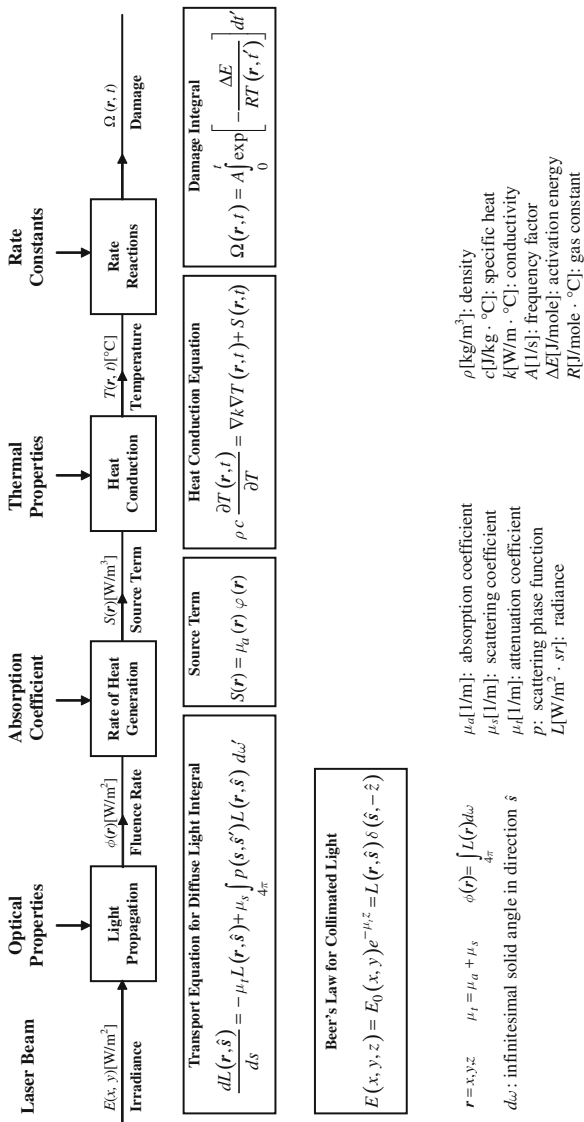


Fig. 1.1 Block diagram of optical and thermal laser tissue interactions. Equations are developed in the various chapters describing tissue optics and thermal interactions

The resulting temperature increase $\Delta T(\mathbf{r}, t)$ produced by the absorbed light and the diffusion of heat to colder regions is given by the heat conduction equation [2] (Chapter 10). Increasing tissue temperature increases reaction rates that can lead to tissue denaturation. These rate processes are represented in the damage integral Ω , based on the first order Arrhenius equation. The block diagram of Fig. 1.1 illustrates that the accuracy of solutions for a particular response is dependent upon the accuracy of the solution of previous events. That is, computation of damage requires accurate predictions of temperature with time which requires knowledge of the rate of heat production which, in turn, is dependent upon an accurate estimate of the fluence rate throughout the tissue. All of these computations require specification of laser parameters at the site of radiation and knowledge of the optical and thermal properties and rate constants of the tissue.

Optical and thermal parameters are not constants, but can dynamically change depending upon the condition of the tissue. Temperature, (de)hydration and thermal damage can alter the absorption and scattering properties of tissue. The most striking example is egg albumin. The clear albumin becomes white when heat coagulates the medium. During coagulation, scattering dramatically increases. Thus the optical properties of a tissue may significantly change during laser irradiation (Chapter 9). Also, the thermal properties of tissue are altered somewhat when heated.

Tissue is a complicated medium, and many of the optical-thermal events produced by laser radiation are interdependent. Yet we have found that many of the assumptions used throughout this book to make formulations tractable, produce solutions that reasonably describe the behavior of laser irradiated tissue. Obviously, the mathematical formulations in Fig. 1.1 are not intended to model tissue at the microscopic level. At best these equations represent the macroscopic response of rather idealized tissue. Nevertheless, the governing equations in Fig. 1.1 provide the basis for successful models used for photodynamic therapy dosimetry, photoacoustic imaging and coagulation of enlarged vessels in the treatment of port wine stains.

1.2 Notation

Often, notation in any field may be ambiguous. When standard notations from two fields such as optics and heat transfer are combined, there are several duplications of symbols. In particular, the field of tissue optics suffers from a proliferation of symbols for the same parameters. Even though symbols are defined in each chapter, the list in Table 1.1 is generally followed throughout the book. Most of the optics notation is taken from the ISO Standard on Quantities and Units of Light and Related Electromagnetic Radiation [3]. When this standard is silent, we have tried to select symbols that have appeared in tissue optics literature and do not conflict with standard optical and thermal notation. In a few chapters it has been necessary to assign more than one meaning to a symbol but we hope the meaning is clear in the context of usage. More complete definitions of optical terms are given in Chapter 3, and thermal terms in Chapter 10. The primary source for our definitions is the special report of the International Non-Ionizing Radiation Committee of the International Radiation Protection Association [4].

Table 1.1 Nomenclature

Symbol	Description	Definition	Units
Basic parameters			
A	Area	–	m^2
c	Speed of light	300,000,000	m/s
c_t	Speed of light in tissue	c/n	m/s
k	Wave number	–	1/m
$\hat{n}, \hat{s}, \hat{u}, \hat{v}$	Unit vectors	–	–
r	Position	(x,y,z)	m
t	Time	–	s
v	Velocity	–	m/s
v_s	Speed of sound	–	m/s
V	Volume	–	m^3
ν	Frequency	cycles per second	1/s
λ	Wavelength	–	nm
ω, Ω	Solid angle	–	sr
Basic optical parameters			
C_x, C_y, C_z	Directional cosines	–	–
g	Average (expected) cosine of angle of scattering	$g = \frac{\int_{4\pi} p(\hat{s}, \hat{s}') (\hat{s} \bullet \hat{s}') d\omega'}{\int_{4\pi} p(\hat{s}, \hat{s}') d\omega'}$	–
n	Refractive index	–	–
$p(\hat{s}, \hat{s}')$	Phase function of single scattering	$\int_{4\pi} p(\hat{s}, \hat{s}') d\omega' = 1$	1/sr
r	Surface reflection	r_{ce} for collimated, external; r_{di} for diffuse, internal, etc.	–
R	Remittance, backscattering	subscripts as necessary	–
T	Transmission	subscripts as necessary	–
T_c	Collimated transmission	–	–
T_d	Diffuse transmission	–	–
δ	Penetration depth of collimated light	$\delta = \frac{1}{\mu_t}$ (mean free path for attenuation event)	m
μ_a	Absorption coefficient	probability of absorption per infinitesimal path length Δx is $\mu_a \Delta x$. ($1/\mu_a$ is mean free path length for absorption event)	1/m
μ_s	Scattering coefficient	probability of scattering per infinitesimal path length Δx is $\mu_s \Delta x$. ($1/\mu_s$ is mean free path length for absorption event)	1/m

Table 1.1 (continued)

Symbol	Description	Definition	Units
μ_t	Total attenuation coefficient	probability of an interaction per infinitesimal path length Δx is $\mu_t \Delta x$, $\mu_t = \mu_a + \mu_s$	1/m
Dimensionless parameters			
a	Single particle albedo	$a = \frac{\mu_s}{(\mu_a + \mu_s)}$	–
τ	Optical depth	$\tau = (\mu_s + \mu_a) d$	–
Reduced optical properties			
a'	Reduced albedo	$a' = \frac{\mu'_s}{(\mu'_s + \mu_a)}$	–
δ_{eff}	Effective penetration depth	$\delta_{\text{eff}} = \frac{1}{\mu_{\text{eff}}}$	m
μ_{eff}	Effective attenuation coefficient	$\mu_{\text{eff}} = \sqrt{3\mu_a(\mu_a + \mu'_s)}$	1/m
μ'_s	Reduced scattering coefficient	$\mu'_s = \mu_s(1 - g)$	1/m
μ'_t	Reduced total attenuation coefficient	$\mu'_t = \mu_a + \mu'_s$	1/m
μ_{tr}	Transport attenuation coefficient	$\mu_{tr} = \mu_a + \mu'_s = \mu'_t$	1/m
τ'	Reduced optical depth	$\tau = (\mu'_s + \mu_a) d$	–
Electromagnetic parameters			
$E(\mathbf{r}_1, \mathbf{r}_2)$	Irradiance at point $\mathbf{r}_1, \mathbf{r}_2$	$\int L \cos \theta d\omega$	W/m ²
$L(\mathbf{r}_1, \mathbf{r}_2; \hat{s}, \hat{s}')$	Radiance	–	W/m ² /sr
$I(\hat{s}, \hat{s}')$	Radiant intensity	–	W/sr
$U(\mathbf{r}, t)$	Electric field at the vector position \mathbf{r} and time t	–	V/m
$\Gamma(\mathbf{r}_1, \mathbf{r}_2; t_1, t_2)$	Average mutual coherence function between space-time positions (\mathbf{r}_1, t_1) and (\mathbf{r}_2, t_2)	$U(\mathbf{r}_1, t_1) U(\mathbf{r}_2, t_2)$	W/m ²
Light parameters			
E_0, \mathbf{E}	Irradiance at surface	–	W/m ²
$F_+(\mathbf{r}, \hat{s}_0)$	Flux in positive direction \hat{s}_0	$F_+(\mathbf{r}, \hat{s}_0) = \int_{(2\pi)^+} L(\mathbf{r}, \hat{s})(\hat{s} \cdot \hat{s}_0) d\omega$	W/m ²
$F_-(\mathbf{r}, \hat{s}_0)$	Flux in negative direction \hat{s}_0	$F_-(\mathbf{r}, \hat{s}_0) = \int_{(2\pi)^-} L(\mathbf{r}, \hat{s})(\hat{s} \cdot \hat{s}_0) d\omega$	W/m ²
$\mathbf{F}(\mathbf{r})$	Flux vector	$\mathbf{F}(\mathbf{r}) = \int L(\mathbf{r}, \hat{s}) \hat{s} d\omega$	W/m ²
H	Radiant exposure	$H = \int E dt$	J/m ²

Table 1.1 (continued)

Symbol	Description	Definition	Units
I	Radiant intensity	$I = \int L dA$	W/sr
$L(\mathbf{r}, \hat{s})$	Radiance	$L = \frac{\partial^2 P}{\partial A \partial \omega \cos \theta}$	W/sr·m ²
M	Radiant emittance	$M = \frac{dP}{dA}$	W/m ²
N	Number of photons	–	–
P	Radiant power	$P = \frac{dQ}{dt}$	W
Q	Radiant energy	$Q = h\nu N$	J
W	Radiant energy density	$W = \frac{dQ}{dV}$	J/m ³
ψ	Fluence	$\int \phi dt$	J/m ²
$\phi(\mathbf{r}), \phi_s(\mathbf{r}), \phi_d(\mathbf{r})$	Fluence rate of scattered light	$\phi = \int_{4\pi} L(\mathbf{r}, \hat{s}) d\omega$	W/m ²
ϕ_t	Total fluence rate		W/m ²
$\phi_p(\mathbf{r})$	Fluence rate of primary beam		W/m ²
Thermal and acoustic parameters			
A	Frequency factor	see Chapter 16	1/s
c	Specific heat	see Chapter 10	J/kg·°C
$E_b(T)_{qb}$	Total emissive power of a black body	see Chapters 10, 14	W/m ²
$E_0, \Delta E$	Activation energy	see Chapter 16	J/mole
$E(T)_{qgray}$	Total emissive power of a gray body	see Chapters 10, 14	W/m ²
h	Heat transfer coefficient	see Chapter 10	W/m ² ·°C
k	Thermal conductivity	see Chapter 10	W/m·°C
L_v	Latent heat of vaporization	2.25×10^6 (water at $\rho = 10^3$ kg/m ³ ; $T = 373.1^\circ\text{K}$ $p = 1.0133$ bars)	J/kg
Q	Thermal energy	–	J
p	Pressure	–	Pa, bars, N/m ²
\dot{q}	Heat flux	$\dot{q} = -k \frac{\partial T}{\partial n}$	W/m ²
R	Universal gas constant	$R = 8.32$	J/mole·°C
S	Rate of heat generation	$S = \mu_a \phi$	W/m ³
T	Temperature		°C
w	Perfusion rate		1/s
$W_b(\lambda, T)$	Monochromatic emissive power of a black body		W/m ³
$W(\lambda, T)$	Monochromatic emissive power of a gray body		W/m ³
α	Thermal diffusivity	$\alpha = \frac{k}{\rho c}$	m ² /s
ϵ	Emissivity of a gray body	($\epsilon < 1$)	–
ρ	Density		kg/m ³
Ω	Damage integral	$\Omega(\tau) = A \int_0^\tau \exp\left(-\frac{\Delta E}{RT(\tau)}\right) dt$	–

Table 1.1 (continued)

Symbol	Description	Definition	Units
κ	Isothermal compressibility	$(\sim 5 \times 10^{-10} \text{ Pa}^{-1})$ for water or soft tissue	Pa^{-1}
β	Thermal coefficient of volume expansion	$(\sim 4 \times 10^{-4} \text{ K}^{-1})$ for muscle	K^{-1}
Γ	Grueneisen Parameter		–

Unit conversion and useful constants

$$1 \text{ cal} = 4.185 \text{ J} = 4.185 \times 10^7 \text{ ergs}$$

$$1 \text{ J} = 1 \text{ W} \cdot \text{s}$$

$$h \text{ Planks constant: } 6.6256 \times 10^{-34} \text{ Js}$$

$$L_v \text{ (latent heat of vaporization of water): } 2.25 \times 10^6 \text{ J/kg; } 2.25 \times 10^3 \text{ J/cm}^3$$

$$\rho \text{ (water): } 10^3 \text{ kg/m}^3 = 1.0 \text{ g/cm}^3$$

$$\rho c \text{ (water)} = 4.27 \text{ J/cm}^3 \cdot \text{C}$$

$$\sigma \text{ Stefan-Boltzmann constant: } 5.6697 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$$

$$1 \text{ mmHg} = 133.322368 \text{ Pa (N/m}^2)$$

Solid angle vector integrals over spheres and hemispheres

Let \hat{s} be a unit vector and vectors A and B then

$$1. \int_{4\pi} \hat{s} d\omega = 0$$

$$2. \int_{4\pi} \hat{s} (\hat{s} \cdot A) d\omega = \frac{4\pi}{3} A$$

$$3. \int_{4\pi} \hat{s} (\hat{s} \cdot A) (\hat{s} \cdot B) d\omega = 0$$

$$4. \int_{4\pi} (\hat{s} \cdot B) (\hat{s} \cdot A) d\omega = \frac{4\pi}{3} (A \cdot B)$$

$$5. \int_{2\pi} \hat{s} d\omega = \pi \hat{z}$$

$$6. \int_{2\pi} \hat{s} d\omega = \pi (-\hat{z})$$

$$7. \frac{1}{4\pi} \int_{2\pi} (\hat{s} \cdot \hat{z}) d\omega = 1/4$$

$$8. \frac{1}{4\pi} \int_{2\pi} (-\hat{z} \cdot \hat{s}) d\omega = 1/4$$

$$9. \int_{2\pi} (\hat{z} \cdot \hat{s}) \hat{s} d\omega = \frac{2\pi}{3} \hat{z}$$

$$10. \int_{2\pi} (-\hat{z} \cdot \hat{s}) \hat{s} d\omega = \frac{2\pi}{3} (-\hat{z})$$

1.3 Format of Book

In this book, we have assumed that tissue, or at least regions of tissue, can be represented as a homogeneous medium. In Part I (Tissue Optics), we assume this medium consists of bulk absorption and randomly distributed scattering centers that

are sufficiently far apart that interactions at one center are independent of interactions at neighboring centers. With this model, it has been possible to use the transport integro-differential equation to describe light propagation in tissue. This theory has been extended to multiple layers, and by employing numerical Monte Carlo techniques it is possible to predict fluence rates in a volume of tissue that contains other structures (such as blood vessels). It is currently unknown how a 'true' theoretical solution based upon Maxwell's equations would compare with the transport solution. Nevertheless, single scattering, Mie theory and the relation between Electromagnetic Theory and Transport Theory are discussed in [Chapters 4](#) and [7](#). No matter which model is used, the results are no better than the values of optical properties used to represent tissue. Methods are presented for measuring the absorption and scattering parameters of tissue. Interstitial measurements of fluence rate using fiber optic probes do agree with predictions of fluence rate in the diffusion region.

In Part II (Thermal Interactions), the rate of heat generation and resulting temperature fields are estimated once the light fluence rate is determined. The thermal response of tissue is estimated using various solutions to the heat conduction equation. Methods for temperature measurement provide critical information for experimentally determining temperature fields in laser irradiated tissue. Other chapters in Part II describe thermal denaturation processes, pulsed laser tissue interaction, and pulsed ablation.

Part III of this book (Medical Applications) contains applications of optical and thermal tissue interactions to various medical problems. How the optical properties of tissue impact fluorescence line shapes is one of the examples discussed. Several chapters are used to describe diagnostic and therapeutic applications of lasers, i.e., opto-acoustic and molecular imaging, OCT, and forensic optics, a recent new field in biomedical optics. Therapeutic applications include laser treatment of port wine stains and light stimulation of nerves.

References

1. Ishimaru A. *Wave propagation and scattering in random media. Vol. 1: Single scattering and transport theory*. Academic, New York (1978).
2. Carslaw HS and Jaeger JC. *Conduction of heat in solids*. University Press, Oxford, 2nd edition (1959).
3. Quantities and units of light and related electromagnetic radiations. International Organization for Standards, ISO 31/6-1980 (E).
4. Review of concepts, quantities, units and terminology for non-ionizing radiation protection: A report of the International Non-Ionizing Radiation Committee of the International Radiation Protection Association. *Health Phys.*, 49(6):1329–1362 (1985).