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Review Article

Laser-Tissue Interaction

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Abstract

Introduction: Understanding the fundamentals of laser light, the optical properties of biological tissues and light-tissue interaction, is essential for all health professionals wishing to work with lasers.

Aim: We will present some important factors that directly or indirectly affect the interaction of light with tissues.

Method: We will utilize scientific sources from PubMed, Google Scholar and other fonts of publications and illustrations.

Discussion: We will discuss how some characteristics of laser light and the optical properties of biological tissue and matter, can govern their interaction.

Conclusion: The complexity of the optical properties of light and biological tissue and their interactive behavior, makes biophotonics a challenging science. A minimum understanding, however, is necessary when utilizing this biotechnology. The specific optical properties of the tissue that will be receiving the specific light, will dictate which laser parameters and treatment protocols are best for the interaction to produce the best outcome and in the safest way. The recently accelerated new discoveries in the field of lasers, have stimulated the rising interest observed in the science of biophotonics. The driving forces for the exploration of this biotechnology are constantly allowing new applications to be explored and providing new aspirations for future capabilities previously unthought-of.

Keywords: *Biophotonics; Laser-Tissue Interaction; Light-Matter Interaction; Optical Properties of Light; Optical Properties of Tissues; Optical Properties of Matter; Laser Parameters; Laser Characteristics; Dental Laser; Laser; Wavelengths; Physics; Photonics; Diode Laser; Electromagnetic Radiation; BPMT; LLLT; Laser; LED; Light-therapy; Dose; Fluence; Fluency Rate; Energy Density*

Introduction

Light-induced therapies are currently used in most fields of medicine and dentistry, including cancer treatment.

The characteristics of the electromagnetic radiation and the optical properties of biological tissue and matter need to be considered, for optimizing this light-interaction and produce the best treatment outcome for the patient.

Understanding energy and some fundamental concepts of optics, sets the foundation for comprehending laser-tissue interaction. Light interacts in many ways with biological tissues. This can be observed in simple daily phenomena, like the production of melanin or synthesis of vitamin D, as a result of the skin reacting to light.

Light interaction with matter is influenced by the recipient's optical properties; when light is applied to the biological tissues, it can undergo absorption, scattering, penetration (transmission) and fluorescence (reflection), to various degrees, and the tissue will produce different responses to the light it absorbs.

Laser-tissue interaction is highly complex, and laser parameters widely influence the biological tissue response. For years, studies have been demonstrating various cellular responses to different lasers, such as the increase of mast cell numbers and degranulation [1], the enhancement of procollagen production in human skin fibroblast cultures [2] and the stimulation of fibroblast proliferation and macrophage responsiveness [3]. As early as 1989, studies demonstrated that the irradiation with monochromatic visible light in the blue, red and far red regions can enhance metabolic processes in the cell and suggested that the photobiological effects of stimulation depend on the wavelengths, dose and intensity of the light [4].

Parameters

Parameters affecting light-tissue interaction in laser therapy have been classified, by Brown RGW., *et al*. as: Laser Variables: Laser Power; Light Delivery Protocol; Power Density; Profile of the Beam: Gaussian Beam Profile, Top-Hat Beam Profile; Irradiation Spot Size, and Energy Density of a Light Source, Local Beam Angle of Incidence with the Tissue, Collimated or Diffuse Irradiation, Light wavelength, Pulse Repetition Rate, Pulse Length, Light Delivery Pulse Modulation and Tissue variables: Optical Properties of the Tissue; Tissue Index of Refraction; Surface Contour; Depth of Targeted Tissue; Tissue Temperature; Thermodynamic Tissue Properties; Tissue Blood Flow and Blood Content [5].

Penetration

An illustration of the wavelength dependence of light on the tissue penetration, can be demonstrated in a study on transcranial low-level laser therapy (LLLT), that compared the fluence distribution, penetration depth and the intensity of laser-tissue-interaction within brain, utilizing the Monte Carlo modeling and visible human phantom, at various wavelengths. They reported a better performance with 660 nm, immediately followed by 810 nm. The 810 nm performed much better than the 980 and 1064 nanometers, with much stronger, deeper and wider photon penetration into cerebral tissue [6]. The wavelength dependence of laser light in biological tissue's depth of penetration, has been well reported in the literature [1,7,9].

Absorption

Optical absorption and scattering coefficients, anisotropy, reduced scattering index, refractive index, light diffusion, reflection of multi-scattered light, are all optical properties that affects light absorption by the light receptors (chromophores) and this has been used in many studies for prediction of the optical behavior of biological tissues [8]. In order for laser light to produce an effect on a tissue, it needs to be absorbed. Light wavelengths, in the visible light spectrum, have been shown to be more readily absorbed than those on the infrared spectrum [1,9].

Tissue Constitution

The *in-vivo* optical properties variation is tissue-type dependent, and the overall trend of the absorption spectra has been described to be a function of wavelength. A main factor, which affects the accuracy of the determined fluence rates in tissue, is the heterogeneous optical properties distribution. The impact of optical properties on light fluence rate is also dependent on tissue geometries, including superficial, interstitial, or whether located within a cavity. The fluence rate is also a function of the beam radius [10]. Refraction, reflection and back-scattering also affects laser absorption [11]. For the application of any "light" (electromagnetic radiation) therapy, the photons must penetrate the tissue and deposit their energy, via the optical absorption properties of that specific tissue. The varied, presence and number, of absorbing chromophores, such as blood components (Hemoglobin, Oxyhemoglobin), water, melanin, fat, yellow pigments (bilirubin, beta-carotene), in different types of living tissue, and the tissue scattering properties, determine its wavelength dependence

[8]. Pigment-specificity can affect penetration and absorption. Wilson and Jacques found that visible laser light, of short wavelength (between 400 nm and 700 nm) was highly absorbed by melanin, hemoglobin and myoglobin [12], whilst infrared wavelengths have little pigment-specificity and the prime absorbing media are proteins and water [13].

Visible light radiation - High pigment-specificity 400 nm - 700 nm	Infrared radiation - Low pigment-specificity700 nm - 1 mm	600-1100 nm
Human melanin: 300 - 700 (Peak at 335nm)	water	Water
Oxyhemoglobin		Oxyhemoglobin Deoxyhemoglobin
Deoxyhemoglobin		
myoglobin	Proteins	Proteins
Lipids (fat): 600- 1100 nm		Lipids(fat)/Highest absorption: 900 - 950 nm and 1050 - 1100nm. (Peak at 940 nm)
Yellow pigments: bilirubin, Carotenoids (i.e: Beta-carotene)		
Chlorophyll a & b: (between 400-500 nm and 600 - 700 nm)		

***Table 1**: Chromophores, pigment-specificity and absorption spectra of electromagnetic radiation.*

A study reporting the wavelength dependent behavior of scattering and absorption of light by various biological tissues (brain, bone, soft and fibrous tissues, skin, fat, etc.), presented "formulas for generating the optical properties of a generic tissue, at any wavelength; in the UV, visible and near-IR ranges, based on variable amounts of absorbing chromophores: blood components (Hemoglobin, Oxyhemoglobin), water, melanin, fat, yellow pigments (bilirubin, beta-carotene) and a variable balance between small-scale scatterers and large-scale scatters in the ultrastructure of cells and tissues" [8]. According to this study, this model, would allow for the prediction of expected standard behavior of the optical properties of live tissues, based on their constitution, which yields their optical properties, at any given wavelength. Using optical absorption spectra coefficients of chromophores, optical scattering coefficients, and refraction indexes, to describe standard scattering behavior versus wavelength, he proposes that analyzing these data, on three different wavelengths, is sufficient to predict scattering at all wavelengths in the UV, Visible and Near-IR ranges, based on variable amounts of absorbing chromophores (blood, water, melanin, fat, yellow pigments) and a variable balance between small-scale scatterers and large-scale scatterers in the ultrastructure of cells and tissues. He further suggests that these 3 parameters influence light penetration behavior and this approximate values for the optical properties of generic tissue types enables the use of light transport models to predict optical behavior.

Influence of laser light characteristics on tissue-interaction

The monochromaticity property of laser light, related to its singularity of wavelength, is a determinant factor for the interaction with biological tissue, since it needs to be absorbed in order to interact with any tissue or matter. Biological tissues have light receptors (chromophores) that are highly selective to the wavelength it absorbs. In the case of biological tissues, some common chromophores include hemoglobin, oxyhemoglobin, melanin and water, as discussed above.

The polarized characteristics of laser light also influences this interaction, as different polarizations of light can be absorbed to different degrees by different biological tissue or matter. A study, quantifying the degree of polarization subsequent to passage through various biological tissue, found different propagation degrees for linearly and circularly polarized light. They also, identified regions that demonstrate greater likelihood of preference for polarized light, and, finally, "indicated the structural features in tissue that influence the degree of polarization and the importance of these structures on polarized light propagation". They suggested that the underlying factors for this difference in polarization within different tissue could be attributed to various scattering parameters [14].

For some laser-biological tissue interactions, light coherence is not fundamental. Broad-band lamps and Non-coherent light sources, such as light-emitting diodes (LEDs), have been successfully used in biophotomodulation therapy [15]. In weak incoherent CW light, photoinduced biological processes is triggered via one-photon absorption from a pulsed coherent laser source, or from an incoherent thermal source of electromagnetic radiation, both, using a quantized radiation field [16]. Brumer and Moshe Shapiro, in 2012, stated that "a pulsed coherent laser source has been shown to induce time evolution in the molecule, while the incoherent thermal source of electromagnetic radiation does not". He furthers states that "confusions in the literature regarding this issue are shown to emerge from a lack of appreciation of (a) the proper description of the absorbed photon and of (b) the role of measurement in understanding the process" [16].

A laser can deposit a great amount of energy within a very small area (spot size), due to its collimation property, that allows the emission of non-divergent, parallel rays to generate minimum beam spread as they propagate over a distance. The diameter of the beam influences the amount of energy delivered by the laser, as light energy gets concentrated with the reduction of the beam diameter. Ordinary light is non-collimated. As it travels, its diameter spreads out, the beam spot size increases in diameter, and the light loses energy on its way. With non-collimated light beams, it is difficult to quantify the energy dosage delivered to its target from a distance, unless the beam is in direct contact with the tissue.

Thermal properties of the biological tissues

Boulinois [17] classified laser effects into 4 groups, according to their biological interactions:

(1) Electromechanical effect
(2) Non-thermic effect: (photochemical, photophysical, photobiostimulation/biophotomodulation)
(3) Photo ablative effect
(4) Photothermal effect:
  1. Vaporization
  2. Coagulation
  3. Protein denaturation

Important aspects of laser-tissue interaction to be considered in biomedical studies are the thermal properties of the tissue and the thermal changes, caused by the interaction of light with the tissue. The thermal properties are related to the temperature distribution in the tissue. This is well explained in the study by Ansari., *et al.* where they state that "The transportation of thermal energy in biological tissue includes different phenomenological mechanisms such as thermal conduction, convection, radiation, metabolic activities and phase change, and further point out that a laser can induce multiple effects like coagulation, vaporization, carbonization or melting [18]". In that study, they emphasize that these effects don't depend only on the thermal properties of the biological tissue, but also on the peak power and wavelength of the laser . Their explanation of the process is given as follows: "The vaporization of water occurs at 100°C. In the vaporization, or thermomechanical procedure, the temperature of tissue does not alter within the vaporization phase, and gas bubbles are formed. The propagation of these bubbles, along with the alteration of their volume, causes thermal decomposition of tissue fragments. If all water molecules are vaporized, carbon atoms are released and the adjacent tissues are blackened, causing the presence of smoke. This stage is called carbonization. Finally, beyond 300^{o}C melting might occur [18]". This topic is well explored in the literature [18-21].

The distinct interaction principles of photophysical, photochemical, and photobiological mechanisms and other aspects of laser-tissue interaction is extensive and is also well covered in the literature [10,22-24].

The Future

Ultrafast laser pulse technology, with the exploration of nonlinearity optical engineering, recently allowed the production of lasers that operate at very high speed and support extremely high peak powers. With the innovative use of nonlinearity, it was possible to develop mode-locking technology, and ultrafast fiber lasers technology. A paper discussing the prospects for trends on future laser technology, identified three promising directions: "mode-locked oscillators, that use nonlinearity to enhance performance; systems that use nonlinear pulse propagation to achieve ultrashort pulses without a mode-locked oscillator; and multimode fiber lasers that exploit nonlinearities in space and time to obtain unparalleled control over an electric field", They reported the increasing trend for the prospective applications of ultrafast lasers and underlined that Mode-locked fiber lasers are becoming commonplace in chemistry, biology, and physics laboratories [25]. The increasing number of recent papers in the literature, reporting the potential benefits of the use of low power lasers for photobiomodulation and photodynamic therapy also points to an increased trend towards the use of biophotonics. This reinforces the necessity for health care professionals to seek a minimum understanding of this fast spreading biotechnology [26-30].

Conclusion

Understanding the fundamentals of laser light, the optical properties of biological tissue and light-tissue interaction, is essential for all healthcare professionals wishing to work with lasers. The complexity of the optical properties of light and biological tissue and their interactive behavior, makes biophotonics a challenging science. A minimum understanding, however, is necessary when utilizing this biotechnology. The specific optical properties of the tissue that will be receiving the specific light, will dictate which laser parameters and treatment protocols are best for the interaction to produce the best outcome and in the safest way.

The recently accelerated new discoveries in the field of lasers, have stimulated the rising interest observed in the science of biophotonics. The driving forces for the exploration of this biotechnology are constantly allowing new applications to be explored and providing new aspirations for future capabilities previously unthought-of.

Conflict of Interest

None. This work is independent and has been carried out with no financial support or commercial or monetary interest for any of the authors.

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