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Spectral Dependence of Laser Light on Light-tissue Interactions and its Influence on Laser Therapy: An Experimental Study

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Abstract

This paper aimed to summarize available facts about the spectral influence on reflection, refraction and absorption and to measure relative absorption of different wavelengths. The experiment showed that longer wavelengths lead to decreasing energy absorption and refraction index in the melanin, as well as a reduction of hemoglobin energy absorption. Longer wavelengths increase the probability of the interaction with water particles and its own light absorption. We conclude that reflection and melanin absorption are negligible for wavelengths higher than 1000 nm due to the ability to penetrate higher amounts of energy into the tissue. Additionally, water absorption increases with the longer wavelengths and refraction index and hemoglobin absorption are reduced.

Keywords: Laser light tissue interaction; Wavelength; Laser

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Introduction

Laser light is characterized as coherent, polarized and monochromatic electromagnetic waves [1]. Research provides information on its usage in medicine for both invasive and noninvasive purposes [2]. Laser therapy is a non-invasive application which transfers energy deep into the tissue using wavelengths that range between 400 nm to 1064 nm [3]. Effects of laser therapy include pain relief which is caused by the water absorption of the light and biostimulation induced by the cell energy absorption. Efficacy of the non-invasive application of laser to the tissues depends on photon propagation and fluence rate distribution within irradiated tissues which can be affected by its wavelength [4]. Effects of laser therapy using different wavelengths have been the subject of previous investigations [5-12]. Furthermore, studies only investigated the medical effects of the laser light on specific wavelengths. Comparable reviews on how specific wavelengths of light can affect the efficacy of the therapy are still missing. The main purpose of this study was to to summarize basic interactions between human tissue and laser, optical properties of human tissue and effects of laser light wavelength.

Research Methodology

Literature research

A computerized search of online scientific databases Pubmed, MEDLINE, Springer, Libertpub, Wiley and NCBI was conducted in the period January-April 2019. The review was limited to literature published in English. There was no limitation for publication year. Articles were defined to be relevant for this review if their key words covered the interaction between laser light and human tissue. Furthermore, all articles were selected according to the wavelength of the studied light. Range of interest was defined from 400 nm to 1064 nm which are typical wavelengths used in laser therapy.

Experimental apparatus

The experiment used various samples of optical phantoms with the thickness of 1, 3 and 5 centimeters [13]. Relative energy density was calculated using approximation of the measured values. Laser radiation was emitted from two different devices with the individual wavelengths of 1064 nm, and combined wavelengths of 810 nm and 970 nm. Low pass filter for 950 nm was used for the measurement of 810 nm wavelength. Power was measured by the L40 (TSB01-005) + Vega (TSA01-011) power meter. Measured beam size was common for all measurements to 10 mm in diameter.

Results

Literature research part

Interactions between laser light and human tissue: Light is composed of photons and is characterized by wavelength, which represents the frequency of the electromagnetic waves. Laser light is monochromatic, polarized and coherent energy. Monochromaticity refers energy being used to produce light on only one wavelength, whereas polychromatic light refers to energy that is comprised of more than one wavelength. Stimulating the atoms of the individual material can be achieved by laser light using a defined wavelength. Therefore, the wavelength is directly related to the active medium [14,15].

Light-skin interactions: Human skin is the biological border for the internal structures of the human body. It serves as a mechanical, chemical and optical protection.

Reflection: Reflection is defined as the loss of electromagnetic radiation caused by the difference in the refractive index between the two indices of refraction [16]. Regular reflectance of human skin is between 4% and 7% [17]. Numerical model calculations of transmittance and remittance of the dermal skin section shows decreasing reflection in correlation with higher wavelengths. Decreasing spectral reflectance was shown in measurements which was observed on the human dermis layer [18,19]. Measurement confirms that wavelengths in near-infrared (NIR) (above 1000 nm) lead to less energy loss. The ratio of reflected and transmitted energy decreases [20]. Laser light which is not reflected or absorbed in the medium travels into the deep lying structures.

Refraction (Scattering): Refraction refers to deflection of light beams from a straight trajectory caused by microscopic non-uniformities within the medium. The type of light scattering depends on the size of the interaction particles and the wavelength of incoming light [21]. According to the wavelength of the scattered light, it can be divided into elastic, without loss of energy, or inelastic refraction [22]. The decreasing trend of the scattering index was calculated from measurements of spectral remittance and transmittance of thin dermal sections under conditions appropriate to the application of Kubelka-Munk's theory of radiation transfer [19]. This scattering behavior was also mimicked by the mathematical expression which results to the value 1.5 cm^{-1} for 1064 nm wavelength, which is the minimum value, compared to the 2.16 cm^{-1} for 980 nm and 4.6 cm^{-1} for 810 nm. Decreasing dependency of the wavelength refractive index for different types of human soft tissue was observed [23]. A decrease of refraction index with a longer wavelength was confirmed in previously conducted studies [24,25].

Absorption: Absorption is the process of transferring energy from light to the target substance which results in energy loss and is defined by the absorption coefficient [26]. The main human tissue absorbers of laser light are melanin, hemoglobin and water.

Absorption in melanin: Melanin is a neutral light-absorbing chromophore with a broad absorbing spectra [27,28]. Melanin can be found in the epidermis by approx. 3% for Caucasians, up to 16% for Mediterraneans and 43% for highly pigmented Africans [27]. The energy absorption while passing the epidermis is mostly caused by melanin. Based on this information, absorption of the light increases with the concentration of melanin in the skin. Spectral absorption is the main subject matter of the several studies reviewed. Furthermore, in NIR regions the absorption of melanin's peak is between 300 nm and 400 nm and decreases for longer wavelengths [29-34]. In wavelengths beyond 1100 nm, absorption of melanin is nearly negligible [19]. Melanin absorption can differ individually. Generally based on the mathematical expression from various published studies the threshold exposure for explosive vaporization of melanosomes melanin absorption index for 1064 is 55 cm^{-1} compared to 72 cm^{-1} for 980 nm, 136 cm^{-1} for 810 nm and 228 cm^{-1} for 690 nm [32]. Results for the whole spectrum are shown in **Figure 1.**

Absorption in water: Water is a weak absorbing chromophore in the visible wavelength spectrum but its absorption increases within the NIR and infrared (IR) regions. Water is one of the most prevalent molecules which can be found throughout the whole body, including intracellular and extracellular fluid, plasma and blood [35,36]. Studies shows that water absorption is almost non-existent below 800 nm, the water maximal absorption index for the range 700 nm-900 nm was 0.026 compared to the range 900 nm-1150 nm which had 0.46 [37-39].

Absorption in hemoglobin: Hemoglobin is the main blood component responsible for absorbing and scattering radiation. Actual absorption spectra depends on the state of the hemoglobin, which could be either oxygen rich or poor. The main difference between these two states occurs at wavelengths over 950 nm [40]. According to Tseng et al. absorption of the deoxyhemoglobin decreases continuously from the wavelength value of 900 nm [39]. Both of the hemoglobin states have maximal peaks of absorption in the near infrared range at wavelengths of 600 nm. Spectral absorption coefficients for the range 650 nm-1042 nm were measured and can be approximated to the range 1200 nm [41]. Results for the specific wavelengths are shown in the **Table 1.**

Experimental part

Relative absorption of the energy was measured for wavelengths.

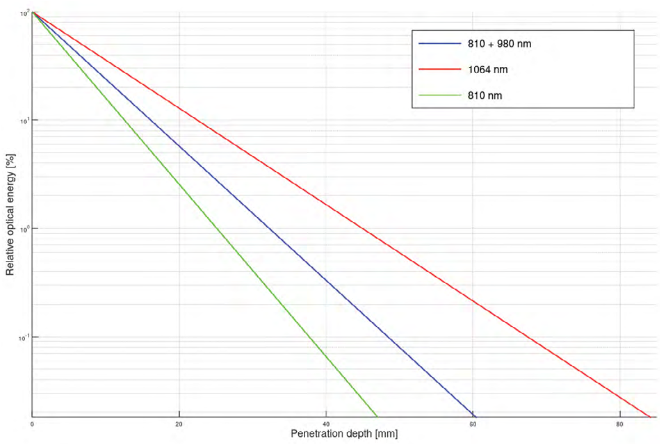

Figure 1 The maximal achievable penetration depth based for different wavelengths.

Main percentual difference was observed on the sample layer of 6.17 mm thickness where 47% was measured for 1064 nm compared to the 25% for the 810 nm. Minimal difference was measured for the 0.25 mm sample. All measured values are in **Table 2.**

All measured values were used for the mathematical approximation to conclude the maximal achievable penetration depth based on the relative absorption of the energy. For the 810 nm wavelength less than 0.001% of the power pass to the depth beyond 4.8 cm. For the 1064 nm wavelength the power limit of 0.001% can be found in the depth of 8.1 cm.

Discussion

This paper summarizes the interaction of laser light with human tissue and its spectral dependence. Laser light transmission and penetration depends on the structure of the targeted tissue, its optical properties and wavelengths. Decreasing reflection index allows a higher amount of the light that resembles the infrared range to penetrate the human tissue, specifically for the wavelengths above 1000 nm [19,20]. Penetrated light is split by the refraction with the tissue particles into the different directions and decrease the total energy. Probability of the interaction between the light and the particle depends on the size of the particle and light wavelength. Moreover, wavelengths with a shorter wavelength interact with smaller particles which lead to power loss. Decreasing tendency of the refraction index was observed and measured on the different types of the human tissue [21,22]. Spectral dependency of the refraction index was calculated and results show a three times higher refraction index for 810 nm than for 1064 nm. Targeted process of the medical application of laser light is its absorption which converts the light into different types of energy. Absorption is affected by the individual tissue particles which mainly are melanin, hemoglobin and water. Melanin is contained within the epidermis by up to 43% and increases light absorption on the skin. Maximal absorption index was placed in the range of 300 nm and 400 nm [27-34]. However, the difference between wavelengths from 690 nm to 1064 nm was measured and the results confirm the decreasing tendency of the absorption coefficient from 228 cm^{-1} for 690 nm to 55 cm^{-1} for 1064 nm [32]. For wavelengths beyond 1100 nm it is essentially negligible [35]. Water is one of the most prevalent molecules which can be found throughout the whole body with negligible absorption index for wavelengths below 800 nm. Spectral absorption index was measured 20 times higher for the range of 900 nm - 1150 nm compared to the 700 nm - 900 nm [37-40]. Research studies have shown that absorption by hemoglobin is strongly spectral dependent due to a maximum absorption for NIR in 600 nm. Measurements confirmed the decreasing tendency of the spectral absorption of deoxy hemoglobin from 3.74 cm^{-1} (650 nm) to 0.08 cm^{-1} for 1064 nm [41].

Table 1 Absorption index for oxyhemoglobin and deoxyhemoglobin for specifics wavelengths.

Wavelength [nm]	OxyHGb [cm^{-1}]	DeoxyHGb [cm^{-1}]
650	0.5	3.74
700	1.79	0.42
750	1.57	0.6
810	0.92	0.79
850	1.11	0.78
900	1.24	0.88
980	1.18	0.49
1000	1.1	0.26
1050	0.88	0.12
1064	0.84	0.08

Table 2 The amount of relative energy delivered to different depths of penetration.

Parameters	The amount of relative energy delivered to different depths of penetration		
Wavelength	0.25 mm	2.35 mm	6.17 mm
810 nm	79.21% ± 0.58%	51.49% ± 0.58%	25.74% ± 1.00%
810 nm + 970 nm	88.45% ± 1.00%	64.94% ± 1.53%	36.65% ± 1.53%
1064 nm	89.24% ± 1.00%	71.71% ± 0.58%	47.41% ± 1.53%

Experimental part of this study measured the relative absorption and calculated the maximal achievable penetration depth. Measured values confirmed the phenomena of increased penetration depth for the wavelength of 1064 nm. Maximal penetration depth was calculated to 8.1 cm which reach a minimum 0.001% of the energy which is almost two times deeper than 4.8 cm for the 810 nm wavelength. Minimum difference was measured in the sample of thickness 0.25 mm.

Conclusion

For laser light on the wavelength of 1064 nm, reflection is negligible. Refraction index is three times lower for 1064 nm (1.5 cm^{-1}) compared to the 810 nm (4.6 cm^{-1}). This allows for a higher amount of energy to be delivered into the tissue. Melanin absorption coefficient decreases from 690 nm (228 cm^{-1}) to 1064 nm (55 cm^{-1}) and reduces the energy loss in the skin. Decreasing absorption index of the hemoglobin from 3.74 cm^{-1} (650 nm) to 0.08 cm^{-1} for 1064 nm presents a strong spectral dependency. Spectral dependency of the water absorption was confirmed and measured 20 times higher in the range of 900 nm - 1150 nm compared to 700 nm - 900 nm. Experimental analysis confirmed the deeper penetration of the 1064 nm wavelength compared to the 810 nm and 970 nm.

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