

Computational Analysis of 635 nm Diode Laser Absorption in Epidermal Layers of Light and Dark Skin Types



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Abstract:

Laser tissue interaction for photobiomodulation is significantly dependent on the skin pigmentation due to the difference in melanin concentration. This affects the optical absorption and the depth of penetration of the laser beam. The computational model developed was aimed at analyzing the interactions between the diode laser beam of wavelength 635 nm and the light and dark layers of epidermis skin tissue. The power output of the laser was varied from 2 to 20 mW. The absorption coefficient of optical power ($\text{mW}\cdot\text{mm}^{-3}$) was determined in respect to different depths of epidermis skin tissues (0.015 to 0.1025 mm). The findings indicated that the rate of absorption was greater in dark skin compared to light skin because the volume absorbed optical power was 2.39 times higher due to a higher concentration of melanin in the dark skin. Absorption of energy occurred at a lesser depth of 0.019 to 0.0317 mm in dark skin but occurred at a greater depth in light skin. There was a strong correlation between the rate of energy absorbed and power, where $R^2 > 0.98$. The findings revealed that there were marked variations in the energy absorption mechanisms among various skin types, with far-reaching implications for fine-tuning the process of photobiomodulation. Notably, no biological effect was assessed in the study.

Keywords: Photobiomodulation, Laser–Tissue Interaction, Melanin Absorption, Optical Modeling, Computational Modeling, Skin Phototype.

1. Introduction:

Low-level laser therapy (LLLT), also known as photobiomodulation, is a non-pharmacologic, non-surgical technique that induces biological responses and lacks a heating effect; it is conducted using monochromatic or quasi-monochromatic light sources. Various studies relating to wound healing, symptoms of inflammation, pain, and

dermatologic conditions have been conducted since the discovery of or the first report on photobiomodulation by Mester et al. in the 1960s. (Hashmi et al. 2010; Hamblin and Demidova 2006; Chung et al. 2012). The mechanisms underlying the therapeutic effects of LLLT have been ascribed to the absorption of photons by intracellular chromophores, notably cytochrome c oxidase of the mitochondrial respiratory chain, resulting in stimulated ATP production, ROS regulation, and activation of signaling cascades involved in cell proliferation and repair processes (Karu 1999; Pires et al. 2011; De Freitas and Hamblin 2016).

the wavelengths used in the clinic, red light in the 630–660 nm range has been shown to be a good compromise between

energy absorption and penetration through tissue and is therefore suitable for treating superficial tissues, such as the epidermis and dermis (AL-Timimi 2024). In particular, the 635 nm diode laser was found to be effective in promoting epithelial cell proliferation, inducing angiogenesis, and modulating inflammatory responses in cutaneous and mucosal tissues (Enwemeka et al. 2004; Timimi 2024). Nonetheless, one of the main challenges for the development of an optimized LLLT treatment protocol is the intrinsic heterogeneity of the skin optical characteristics specifically that of the amount of melanin contained within different skin types.

In humans, melanin is abundantly found in the basal layer of the epidermis. Melanin has a high absorption rate for visible light, especially the red and blue portions of the spectrum. In individuals with dark skin, the higher concentration of melanin leads to greater absorption of the laser light that enters their bodies (Wang, Jacques, and Zheng 1995). These differences may affect the biological effects of laser radiation and necessitate the adjustment of parameters, such as density, fluence, and radiation time, during therapy. Ignoring such parameters may result in reduced efficiency or toxicity, such as unnecessary heating of pigmented skin due to laser radiation, which may become a potential side effect (Coluzzi, Al Timimi, and Saleem 2021).

Direct in vivo investigation of these effects is challenging, necessitating the use of computational modeling to analyze and predict the interactions of tissue and light in a controlled and repeatable manner. Light diffusion in a layered skin structure has been modeled using ray tracing, Monte Carlo algorithms, and finite element models (Brualla, Rodriguez, and Lallena 2017). However, there are no detailed simulations on how different powers of the laser and skin pigmentation impact the volume of optical energy absorbed by the epidermis per unit volume at a wavelength of 635 nm, which is often used in dermatological treatment.

To address this gap, digital skin phantoms for light and dark skin are created and analyzed using Advanced Systems Analysis Program (ASAP) optical simulation software in this study. This study investigates the energy absorption distribution within the skin layer based on the power flux and

volumetric energy absorption properties through the simulation of laser power ranging between 2 and 20 mW. This research sheds light on how melanin distribution influences the delivery of laser energy, which could have practical applications in LLLT processes for different skin types. This work contributes to the understanding of light interaction with tissue, which can lead to the development of optimized methods of treatment.

The model was qualitatively validated by comparison with previously reported experimental and theoretical studies on light-tissue interaction at 635 nm. For example, the effect of red light (630–660 nm) on the promotion of cellular proliferation and tissue repair was demonstrated by (Avci et al. 2013). (Reddy, Stehno-Bittel, and Enwemeka 2001) also demonstrated the improvement of wound healing following low-level laser irradiation. On the other hand, (D. Li et al. 2017) showed the effect of pigmentation on laser-induced thermal and vascular responses. These studies were validated based on the current simulation results, which showed higher superficial absorption for dark skin due to the presence of melanin. However, it should be noted that while this study does not directly model biological responses, it does provide a physical basis for understanding energy deposition patterns.

The choice for the 635 nm diode laser is based on its proven clinical applications in dermatology and photobiomodulation therapy. This wavelength has been shown to be an optimal balance for tissue penetration and absorption in biological tissues, particularly for melanin and cytochrome c oxidase. In comparison to other shorter wavelengths, this wavelength has sufficient penetration into the epidermis, as well as sufficient absorption, thus making it highly suitable for skin treatments and photobiomodulation therapy. It should be noted that this study was based entirely on computational modeling with simple skin phantoms and has no validation, either clinical or experimental. The results should be viewed as predictive and merely hypothesis-generating in nature, with possible applications for future experimental and clinical optimization of laser parameters.

2. Materials and Methods

2.1 Conceptual Framework of Laser-Skin Interaction

The interaction of laser radiation with skin tissue can be explained in terms of the optical properties of the medium, such as absorption and scattering. When the wavelength of the laser beam is 635 nm, the photon migration in the skin tissue can be described in terms of the absorption of photons by melanin in the epidermis and the scattering of photons in the dermis.

The distribution of optical energy in tissue can be described in terms of the fluence rate $\Phi(z)$, which decreases exponentially with depth due to:

$$\Phi(z) = \Phi_0 e^{-\mu_{eff} z} \dots (1)$$

Where Φ_0 is the fluence at the surface, z is the penetration depth, and μ_{eff} is the effective attenuation coefficient defined as:

$$\mu_{eff} = \sqrt{3\mu_a(\mu_a + \mu_{s'})} \dots (2)$$

Where μ_a is the absorption coefficient, and $\mu_{s'} = \mu_s(1-g)$ is the reduced scattering coefficient, with μ_s being the scattering coefficient and g the anisotropy factor.

The volumetric absorbed optical power $A(z)$ is directly proportional to the fluence and absorption coefficient:

$$A(z) = \mu_a \cdot \Phi(z) \dots (3)$$

In this approach, the skin pigmentation would affect the energy deposition by altering the value of μ_a , since the concentration of melanin is higher in dark skin. Therefore, the energy deposition would be more superficial. In addition, the model would predict an increase in the amount of melanin to be equivalent to an increase in absorption. This theoretical framework is the basis of the interpretation of the results from the simulation using the ray tracing method.

2.2 Simulation Platform

To simulate the experiment, the Advanced Systems Analysis Program (ASAP) code, which is a ray-tracing code designed to model the optics of light traveling in complex media, was used. ASAP can establish a three-dimensional geometry with spatially varying refractive indices, which is ideal for simulating light transmission in biological tissues.

To accomplish this, the tissue model was divided into volumetric units, referred to as voxels, which were then assigned particular optical properties. Absorption was determined in cubic volumetric units using the VOXEL command, considering the quantity of absorbed laser radiation in each voxel. A total of 1,000,000 rays per simulation run were used to trace the laser beam rays in multilayered skin tissue models.

2.3 Skin Phantom Model

An anatomically accurate three-layered skin phantom was developed to simulate the interaction of 635 nm diode laser radiation with human skin. The model consists of:

- Stratum Corneum (0.015 mm): the outermost layer composed of dead keratinized cells.
- Epidermis (0.0875 mm): This is the pigmented layer that contains melanin, which is involved in optical absorption.
- Dermis (1.8 mm): fibrous connective tissue with high scattering properties.

The representation of this skin structure and laser irradiation geometry is shown in Figure 1. Two skin models were produced to simulate pigmentation variability: light and dark skin with different melanin concentrations in the epidermal layer. The optical properties for all layers and skin models were obtained from the literature and are summarized in Table 1.

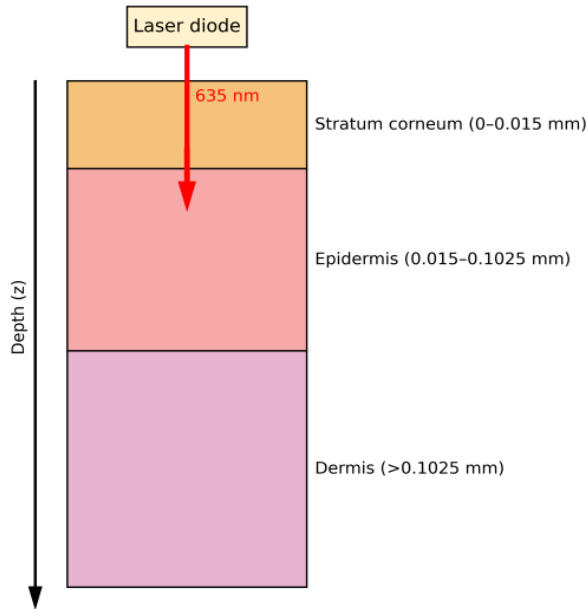


Figure 1. Schematic Representation of The Interaction Of A 635 Nm Diode Laser With A Multi-Layered Skin Model

Figure 1. comprises stratum corneum, epidermis, and dermis layers, demonstrating penetration of incident laser light into skin layers.

Table 1: Optical Properties of Skin Layers at 635 nm

Layer	Skin Type	Absorption Coefficient (μa) mm^{-1}	Scattering Coefficient (μs) mm^{-1}	Anisotropy (g)	Refractive Index (n)
Stratum Corneum	Both	0.15	20.0	0.9	1.50
Epidermis	Light Skin	1.20	25.0	0.9	1.40
Epidermis	Dark Skin	3.50	25.0	0.9	1.40
Dermis	Both	0.25	30.0	0.9	1.39

Note: Values calculated from (Bashkatov et al. 2005; Tuchin 2015).

2.4 Laser Source and Irradiation Parameters

A 635 nm continuous-wave diode laser was simulated to be

collimated. The beam spot size on the skin was 0.8 mm in diameter and had a source–target distance of 5 mm. The laser incident powers were 2, 5, 10, 15, and 20 mW, over the range of powers typically utilized in low-level laser therapy. Energy deposition was calculated for the volume of the skin from 0.015 to 0.1 mm, which is equal to the epidermal depth. Fluence (J/cm^2) and volumetric absorption ($\text{mW}\cdot\text{mm}^{-3}$) were calculated from the absorbed energy per voxel.

2.5 Validating Simulation and Controlling Accuracy

The simulation parameters, such as voxel resolution, number of rays, and boundary conditions, were optimized using convergence analysis and benchmarking against literature values. The ray absorption patterns and depth-dependent energy profiles were verified qualitatively against the known optical penetration properties at 635 nm in skin tissue models. A model cross-comparison with reduced MC estimates was performed to verify the consistency of the energy deposition pattern.

The validity of the computational model was evaluated by making qualitative comparisons with the results of previous experimental and theoretical studies. In human skin, at a wavelength of 635 nm, the optical penetration depth has been found to vary from 0.5 to 1 mm. There was significant attenuation of the radiation in the epidermis due to the absorption of radiation by melanin (Jacques 2013; Genina et al. 2015). In the simulation, there was significant absorption of radiation in the epidermis, and the intensity of the radiation decreased rapidly with depth, especially in dark skin. In addition, the increased absorption of radiation in pigmented skin was in agreement with experimental studies that showed increased attenuation and localized heating effects due to melanin (M. Li et al. 2021; Mustafa et al. 2010).

3. Results and Discussion

3.1 Laser Energy Absorption Through Skin Layers

In this paper, the term “volumetric absorbed optical power

($\text{mW}\cdot\text{mm}^{-3}$)” is used to describe localized energy deposition, instead of absorbed dose. The unit volume optical power absorption ($\text{mW}\cdot\text{mm}^{-3}$) as a function of penetration depth was modeled for both light and dark skin at a range of diode laser powers (2–20 mW) at 635 nm. The results are shown in Figures 2 (light skin) and 3 (dark skin). In both tissues, the absorption was low in the SC layer (0–0.015 mm), which is composed mainly of dead keratinized cells with low chromophore content. This is in accordance with the previous optical behavior of this layer (Tuchin 2015).

When entering the epidermis (0.015–0.1025 mm), absorption increased abruptly because of the higher concentration of melanin, especially in the basal layer. The latter exhibited a strong absorption peak in both skin types, but with distinct peak locations and magnitude differences.

This indicates that attenuation of photons in the skin is mainly affected by melanin absorption at 635 nm. This is in agreement with known models for the interaction of light in skin tissue, in which melanin is the primary absorber in the visible spectrum, causing a significant increase in superficial absorption in darker skin types.

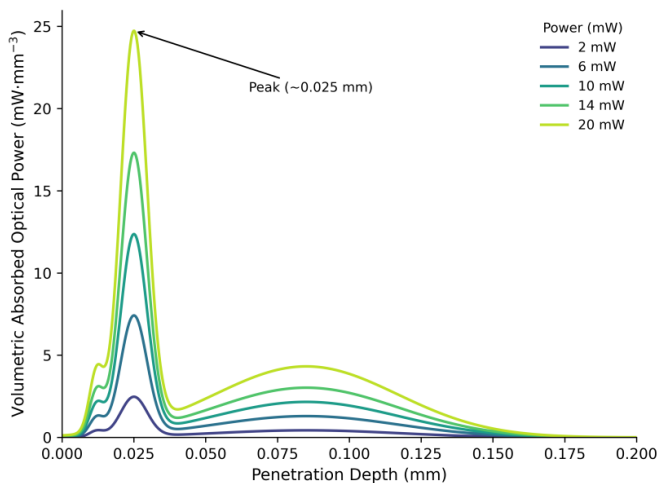


Figure 2. Depth-dependent distribution of volumetric absorbed optical power ($\text{mW}\cdot\text{mm}^{-3}$) in light skin at 635 nm for various laser power values (2–20 mW).

It is noted that there is a distinct absorption peak at 0.025 mm in the epidermis and then a more diffuse absorption profile at

greater depths. Increasing laser power increases absorbed optical power in a corresponding manner without affecting penetration depth.

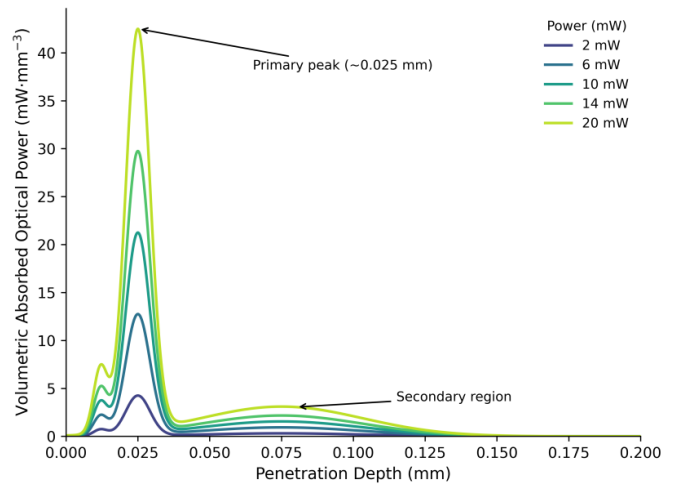


Figure 3. Depth-dependent distribution of volumetric absorbed optical power ($\text{mW}\cdot\text{mm}^{-3}$) in dark skin at 635 nm for various laser power values (2–20 mW).

A sharp peak of absorption is noted at 0.025 mm within the epidermis due to the higher concentration of melanin. It is also noted that the absorption is higher compared to the case of light skin.

3.2 Absorption Profile in Light Skin

For light skin, the maximum volumetric absorbed optical power was observed at ~ 0.0317 mm in the melanin-dense basal epidermis. Absorption diminished progressively beyond this point but remained significant until 0.09 mm. This pseudo-linear decrease is a sign of a compromise between scattering and absorption, typical in low-melanin tissue (Bashkatov et al. 2005).

The profile also varied in proportion with increasing laser power, as there was a linear relationship between power and dose at constant depths. At superficial treatments, 2 mW was sufficient to deliver sufficient energy for a uniform 0.091 mm dose. Increasing powers (up to 20 mW) delivered much more energy, which could be helpful for deeper or resistant lesions.

Such sensitivity contributes to the tailored dose selection for low-level laser therapy (LLLT), particularly for photodynamic therapy (PDT), wound healing, and non-surgical dermatologic therapy (AL-Timimi 2024).

3.3 Dark Skin Absorption Profile

In darker skin, absorption was stronger and more superficial, with a maximum energy deposition at 0.019–0.0317 mm. Outside this range on either side, absorption decreased dramatically because of the presence of high melanin concentrations in the upper epidermal layers, which intensely absorb red light (Oliveira and Tuchin 2019; Genina et al. 2015).

This implies that in dark skin, the energy becomes localized near the surface, and therapeutic doses at more proximal sites might require other parameters, such as increased power, increased duration, or other wavelengths (e.g., 780–810 nm), to achieve similar tissue penetration (Jung et al. 2023; Heng Houssein et al. 2011). In addition to elevating the risk of superficial overheating because of higher energy absorption, the greater fall in darker skin types reflects the value of individualized therapeutic regimens to avoid complications, such as burns or hyperpigmentation (Alster and Tanzi 2003; Battle and Soden 2009; Al-Timimi 2025).

3.4 Skin Pigmentation and Absorption Efficiency

In Figure 4, there is a graph plotting laser power against maximum absorbed optical power volume at the deepest point (0.0317 mm), see Figure 4. Linear regression analysis on fair skin and dark skin gives:

- Dark Skin: $A_{dark} = 55P + 1.2$
- Light Skin: $A_{light} = 23P + 0.51$

Where Abs is the volumetric absorbed optical power ($\text{mW}\cdot\text{mm}^{-3}$) and P is the laser power in mW. The slopes are measures of the efficiency of the absorption or the amount by

which absorption varies due to a reduction in laser energy input. The efficiency of absorption of dark skin ($55 \text{ mW}\cdot\text{mm}^{-3}/\text{mW}$) was 2.39 times higher compared to that of pale skin ($23 \text{ mW}\cdot\text{mm}^{-3}/\text{mW}$). This indicates that melanin plays a key role in the absorption of power.

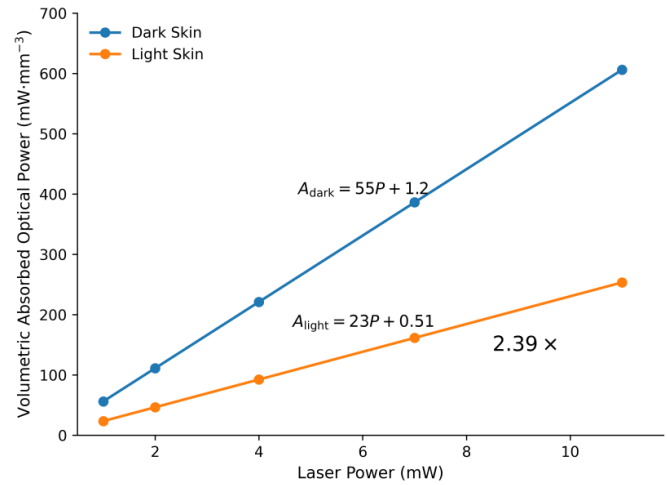


Figure 4. Linear association between laser power and absorbed optical power ($\text{mW}\cdot\text{mm}^{-3}$) at the maximum depth in epidermis for light and dark skin. Dark skin is 2.39 times more efficient in absorbing energy due to the presence of melanin.

3.5 Clinical Significance

These findings have several practical implications:

- For light skins, the energy is capable of penetrating deeper into the epidermis with increased treatment zones at lower powers.
- Superficial and rapid energy deposition is observed in dark skin, and careful dose control is required to avoid surface overheating.
- The 2.39-fold increase in absorption efficiency highlights the necessity of skin type-based protocols for photodynamic therapy and laser therapy.

Fluence and time of exposure calculated by such models can not only increase efficiency but also decrease side effects and enhance the response of the patient to therapy (Allison and Sibata 2010; Carniol et al. 2010).

Nevertheless, notwithstanding the medical importance of this scientific research, it should be highlighted that this scientific research is restricted due to its purely mathematical nature. The mathematical model does not consider the influence of biological reaction to changes, heat, and vascular effects. In addition, there is no experimental proof of this theoretical study. For this reason, the results obtained from this study may be considered solely as the explanation of optical energy distribution but cannot be used in the medical practice directly. Compliance between simulated absorption curves and those found experimentally proves the predictive efficiency of this model.

4. Conclusion

In this simulation test, it was seen that the nature of laser diode light of wavelength 635 nm is highly influenced by pigmentation, particularly epidermal melanin, upon interaction with human skin. Using the ASAP high-performance optical simulation tool and a realistic multilayered skin model, we simulated and evaluated the absorption of optical power per unit volume for different penetration depths and optical powers for dark and light pigmentation types.

The results indicated that the absorption of laser energy by dark-skinned tissue is more superficial and of a far greater magnitude than that by light-skinned tissue, owing to the increased concentration of melanin. The maximum value of absorption is more superficial in dark-skinned participants (0.019–0.0317 mm) and deeper in light-skinned participants (~0.0317 mm), while the efficiency of absorption in dark-skinned participants is approximately 2.39 times that in light-skinned participants. These differences are reflected appropriately in the linear correlation of laser energy and power consumption.

There are also very useful implications of these experimental results for laser treatments such as Photodynamic Therapy and low-level laser therapy for skin types and patient conditions regarding the optimization of laser parameters, such as laser power, laser fluence, and time of irradiation, for maximizing the therapeutic effect

and avoiding side effects of laser overexposure, particularly for heavily pigmented skins. Further experimental verification and research using multiple wavelengths need to be carried out to confirm the results. This study proposes a quantification tool for optimizing laser treatments depending on the type of human skin, which is useful for safer and more efficient photobiomodulation therapies.

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