

FULL PAPER**Thermal Distribution Effect of Picosecond Laser on Facial Rejuvenation****Abstract**

The application of picosecond laser in dermatology was mainly focused on optimizing the treatment of benign skin pigmentation lesions, melasma, photodamage, and scar revision. Rejuvenation therapy has been performed with clinical effects evaluated via histopathological analysis of effects on skin sample biopsy taken from rabbit's dorsal skin.

The goal of this study is the evaluation of the thermal effect of ultra-frequency pulses appeared on a lesion caused by Picosecond laser in invitro rabbit model.

The method used is Picosecond Nd:YAG laser (1064nm/532nm) pulse duration (450ps/380ps) with pulse energy (500mJ/350mJ) and a spot size of (7*7 mm²) had been administrated to rabbit skin, once on one side of the dorsal skin was exposed, and the other side has been appointed to be a control. In this study, samples were grouped into two groups, biopsies of both normal and irradiated skin were taken immediately after the laser irradiation in the first group, and 3 days post irradiation in the second group.

As a result, the laser pulses led to decrease the thickness of epidermis, as well as an increment in the depth of thermal damage. Collagen formation shown most effective using 1064nm pulse duration of 400ps, while the strong effect of irradiated skin increased as the laser power increased.

As a conclusion, photodamage urged by the laser is caused by photothermal factors, which causes heating and vaporizing mechanisms to rejuvenate the epidermis skin layer. The exposed area literally expands and penetrates deep into the dermis skin layer, eventually stimulates collagen coagulation.

Keywords: Picosecond laser, rejuvenation, thermal depth, skin.

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Introduction

In dermatology, the applications of picosecond laser shows encouraging results in skin rejuvenation specially in tattoo removal and in benign pigmented lesions treatment, [Shimojo, 2020].

Irradiation of ultra-short picosecond pulses induces instantaneous heating of skin and causes greater damage due to the increased peak power density, with less harm to the tissues around. Accordingly, picosecond laser skin treatment is more effective and less invasive effect, [Ohshiro T, 2016].

Picosecond laser equipment will continue to be used in aesthetic clinics. Concerning the medical uses of a laser machine, clinical studies are essential to assess the safety and applicability of the therapy. In skin rejuvenation by laser, a light energy is applied to produce the treating efficacy. However, an injury risk may happen to the surrounding areas other than the treatment spot. Because laser therapy should be applied under the safety consideration is the basis for clinical performance. The risk assessment of laser therapy may be done through in-vivo and ex-vivo studies, [Rylander MN, 2011].

Computational and mathematical models are regularly used to predict and study the thermal response of tissues under laser treatments. The models consider factors like heat (generation, conduction, and dissipation) within the tissue, also the role of blood circulation mechanism. The Pennes Bioheat model, which was found in 1948, used as a fundamental basis for understanding the thermal responses of tissues when irradiated by laser, [Feng Xu, 2008].

In this research, we present a computational trial to study the reliability of treatment with a picosecond Nd-YAG laser via mathematical modelling and simulation.

Thermal damage rate, temperature rise and optical penetration depth results from picosecond pulsed laser beam are studied mathematically to evaluate the reliability. The safety perspectives assures that the computational clinical test can achieve the same results provided by the in vivo and clinical tests, [Ma, L., 2023].

Flawless skin is difficult to obtain, the entire human body is covered by skin, and it's the first contact with the environment. That's why, many skin issues occur due to endogenous and exogenous factors, [Ma, L., 2023]. For example, acne appears as a result of the increased secretion of sebum caused by hormonal changes, [Chilicka, K., 2022]. Moreover, living habits, sleep patterns, diet, stress, can effect the appearance of skin acne, [Briganti, S., 2020].

Skin issues such as enlarged pores is referred to sebaceous gland secretion, enlarged hair follicle and skin aging. Enlarged pores make the skin to look dull, loose, and unhealthy, [Ma, L., 2023]. Daily exposure to sunlight causes skin pigmentation and other problems. Hormone levels and genetics can also affect skin pigmentation, [Del Bino, S., 2018].

The fine lines and wrinkles appears while skin is aging as a result of the combined action of both genetic factors and external factors. Obviously, our skin contains millions of microorganisms that makes the skin microbiota, which has an important role in defeating the body against external pathogens, [Byrd, A. L., 2018]. When the bio balance is damaged, different skin problems, such as acne, atopic dermatitis, sensitive skin, etc., will occur eventually, [Farage M. A., 2019].

Thermal Distribution Effect of

Skin is made of three layers:

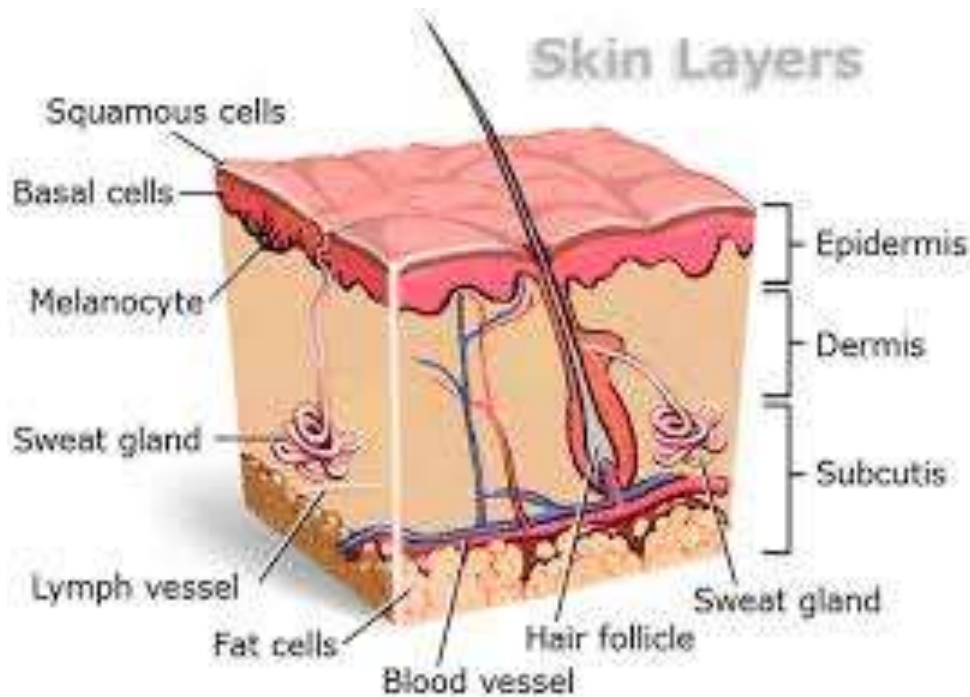


Fig.(1) The main layers of skin

Epidermis

The epidermis thickness is 0.5–1.5mm approximately and it's avascular, as shown in figure (1), the epidermis consist of five epithelial layers, including the stratum corneum, stratum granulosum, stratum lucidum, stratum spinosum, and stratum germinativum or basale, figure (2).

The epidermis is consist of keratinocyte and melanocytes, Langerhans and Merkel cells, [Lopez-Ojeda, W.,2024].

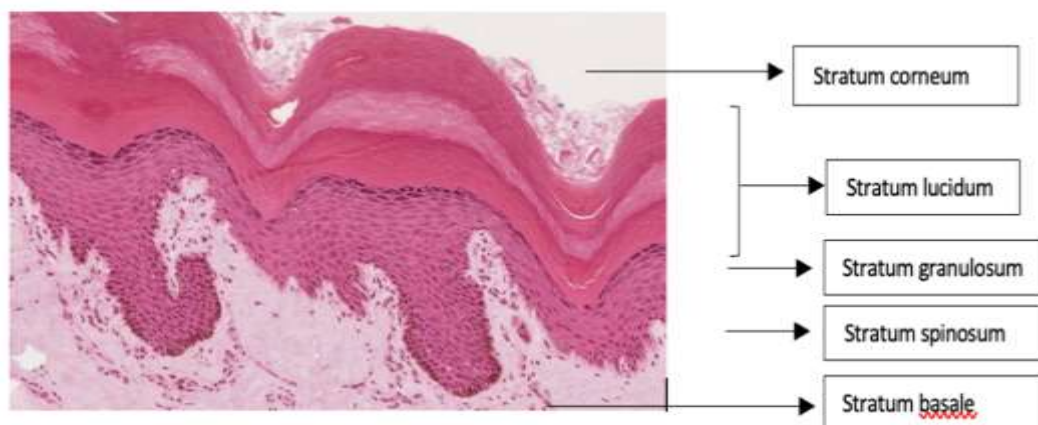


Fig.(2) Composition of epidermis layer of skin

Dermis

Thermal Distribution Effect of

The dermis is an essential part of the integumentary system (dermis= skin), as diverse from the epidermis (epi= upon) and hypodermis (hypo= below), [Honari, G., 2017].

The dermis is a thick layer full of vessels and nerves that nourishes the epidermis, it is composed of areas: the superficial papillary area and the deep reticular area. The superficial area is the thinner upper layer, [Menon G. K., 2002]. It fibroblasts that generates fibronectin and hyaluronic acid (major components of the extracellular matrix), [Fenner, J., 2016]. The deep reticular dermis is the thick deeper layer contains blood vessels and collagen fibers providing a tensile structure to the skin. With ageing, the cells responsible for extracellular matrix decrease, less organized collagen and elastin deposition, causing weaker skin, [Honari, G., 2017].

The most common skin treatments in medical applications, include wrinkle ablation, tattoo removal, tumor removal, scars treating, as shown in figure (3a),(3b), and (3c) below, [Azadgoli, 2016].



Fig.(3) a- Treatment of acne scar by using Picosecond laser, b- Treatment of tattoo removal, c- Treatment of wrinkles.

The deep skin penetration provided by Picosecond Nd-YAG is so essential to achieve dermal rejuvenation to obtain a young aesthetic skin, [Azadgoli, 2016].

Theoretically, the picosecond Nd-YAG laser provides less pain in the process. Since the heat has vanished during skin rejuvenation process after irradiation session, eventually reduces heat in tissues. Other parameters reduce pain, such as short pulse duration, smaller spot size, and lesser irradiation time on the skin. On the other hand, the disadvantage of picosecond Nd-YAG laser leads to a burning effect, which transfer to the area around , [Ungaksornpairote, C., 2020].

Picosecond Nd-YAG laser is used to treat of photoaging appearance, removing wrinkles and leading to regeneration of the dermis via the distribution of the thermal effect, [Ungaksornpairote, C., 2020].

Mathematical Model

Thermal Properties Identification

The variation of heat absorption of the laser beam is defined by the thermal conductivity and the heat capacity of the skin model, and the diffused heat at a speed proportional to the temperature gradient. This diffusion develops a raise in the temperature of normal tissues surround the treatment site which may lead to cell necrosis and coagulation, [Shimojo, 2020].

A mathematical model is presented for the calculation of skin thermal properties. By applying a periodic heating technique is applied to identification of tissue thermal diffusivity, [Bajrami, D., 2024]:

$$a = k / \rho C \quad (1)$$

in $[m^2.s^{-1}]$, where k thermal conductivity $[W.m^{-1}.K^{-1}]$, ρ and C specific heat $[J.kg^{-1}.K^{-1}]$, [Dilhaine et al., 2004].

$$\delta = \sqrt{a/f\pi} \quad (2)$$

where f is the modulation frequency.

The relationship between the thermal distribution (temperature rise) in the skin and the energy of a laser beam can be expressed through heat transfer and laser-tissue interaction principles. The equation governing this can be derived from the Penne's bio-heat equation and laser energy absorption models, [Bajrami, D., 2024]:

$$(3) \quad \rho c \frac{\partial T}{\partial t} = k \nabla^2 T + \dot{Q}_{met} + \dot{Q}_{perf}$$

Where, T is the temperature,

ρ is the density of the tissue, c_p is specific heat capacity, k is thermal conductivity.

$\dot{Q}_{met}$ is the metabolic heat generation/ unit volume, $\dot{Q}_{perf}$ is the heat generated by blood perfusion (which can be expressed as a function of blood flow rate and specific heat of blood).

One common approach is based on the Pennes bio-heat transfer equation, combined with the Beer's law for laser absorption in tissues, [Cheng, Y., 2024].

The laser heat source term T is usually modeled using the Beer-Lambert law:

$$T(z) = \mu_a I_0 e^{-\mu_a z} \quad (4)$$

Where:

$T(z)$: Thermal distribution (W/mm²)

μ_a : Absorption coefficient of the skin tissue (1/mm)

I_0 : Initial laser intensity (W/mm²)

z : Depth in the skin (mm)

Combining these, the energy absorbed by the skin and the resulting thermal distribution depends on the absorption coefficient, laser intensity, and depth, [Cheng, Y., 2024].

For the laser beam of 1064nm, the optical depth of penetration through the skin is 4.315 mm, and for the 523nm laser beam, the depth is 3.051 mm, where the thermal conductivity k of rabbit's skin is 0.21 $[W.m^{-1}.K^{-1}]$, the specific heat C of skin is 3.77 $[J.kg^{-1}.K^{-1}]$ and the volumic density is

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1[kg*m⁻³], by applying the Beer's law with energy of laser beam ranges from 200 to 500 mJ for both optical lengths of the 1064nm 1nd 523nm, the below relation is obtained as shown in figure (4).

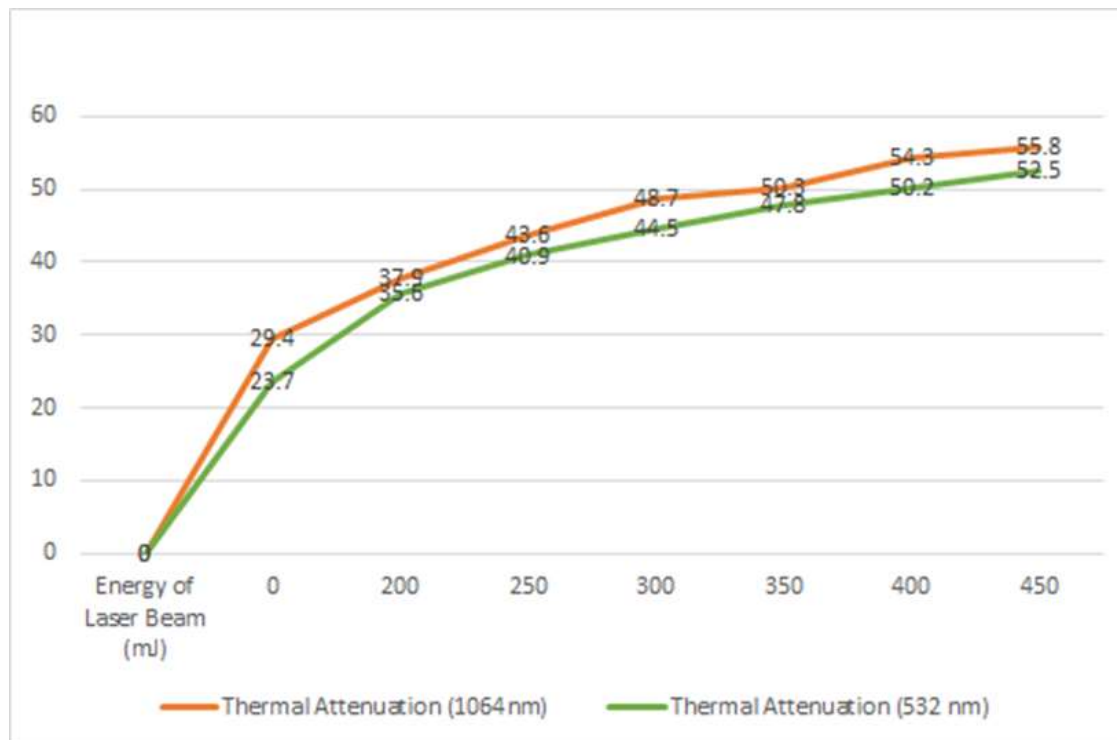


Fig.(4) Relationship of Thermal distribution and the laser beam energy

Experimental Validation

Laser irradiation

The experimental setup used for the laser irradiation procedure on in vivo rabbit skin is presented as 1064nm and 523nm picosecond Nd-YAG laser had been applied to rabbit skin, on one side of the rabbit's dorsal area being exposed, while the other side been used to be a control sample.

In Figure (5). A Picosecond Nd:YAG laser (South Korea's award-winning PicoLO laser technology), which provides a peak power of 1.1 GW, repetition rates of 1–10Hz, and spot size (Zoom 2~7 mm, fractional 7*7~10*10 mm², collimated 20 mm²) was used for the experiment. The skin specimens were divided into two groups and were irradiated with pulse duration of 1064nm frequency, pulse duration 450 ns and 532 nm frequency, pulse duration 380ps, respectively, with energy increment from 350 ~ 500 mJ.



Fig.(5) The PICO picosecond Nd-YAG laser device.

Histological Sample preparation

After irradiation, sample skin have been taken by cutting irradiated spots from the skin, some of them have been taken on the same day, as shown in figures (6) and (7), and some after three days to study the effect of laser doses on the skin samples. All samples have been taken to a histopathology lab for the processing of slide preparation which is done automatically by an automatic tissue processing machine.

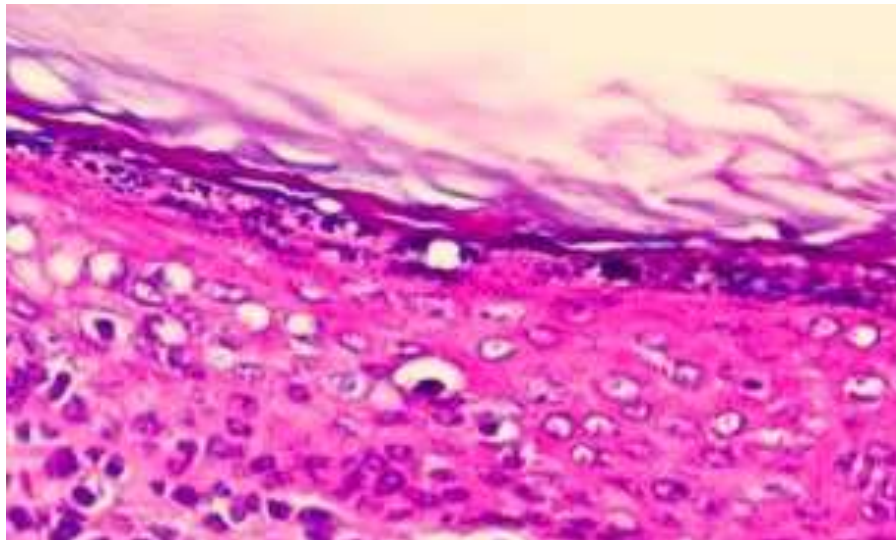


Fig.(6) The skin layers of rabbit skin without irradiation (control sample)

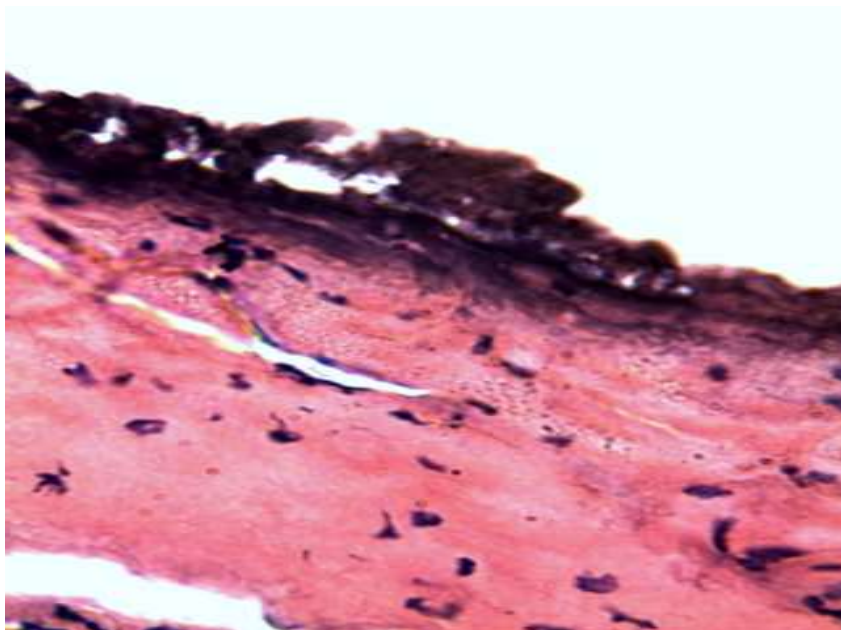


Fig.(7) The skin layers after irradiation and reddening of dermis is obvious

Results and Discussion

Results: the laser pulses tested develop lessening of epidermal thickness and an increment in thermal damage depth. Collagen and Fibrinogen coagulation was noticeably increasing with increasing the

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effective pulses of picosecond Nd-YAG laser, the power of irradiated skin gets higher as the effect of the irradiation increase, as shown in figures (8) and (9)below.

Discussion: The heat been generated from a Picosecond Nd-YAG laser emitting at 1064 nm and 532 nm so as to be distributed within the skin layers, led to increase in fibrinogen cell that are responsible of producing fibrins besides collagen accumulation which improves and rejuvenate the skin texture.

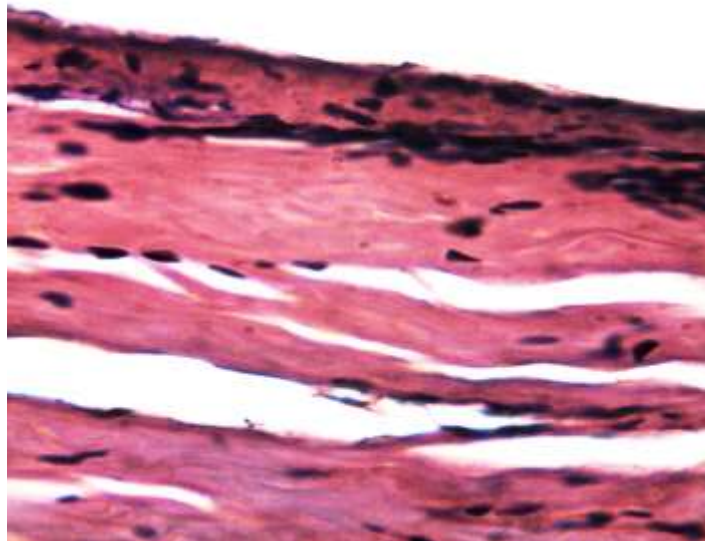


Fig. (8) Rabbit skin after three days of laser irradiation shows the increasing amount of collagen and fibrinogens in the dermis.

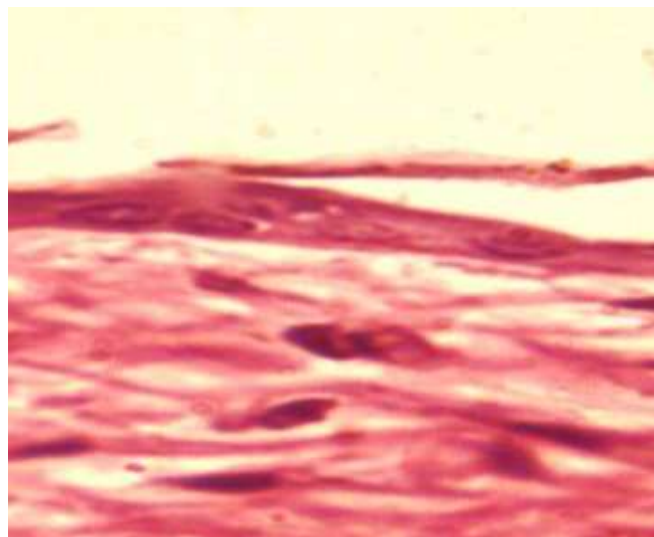


Fig.(9) Rabbit skin with higher magnification under microscope shows the aggregation of collagen and fibrinogens in the dermis.

Conclusion

In this study, the effect of laser irradiation on human skin is investigated. First, a mathematical model has been considered and simulation results are presented. Obtained from previous studies, it has been shown

that in order to validate this predictive model, it is crucial to estimate several model parameters: an optical property (extinction coefficient in human skin) and thermal characteristics of the skin layers (epidermis and dermis).

Thermal properties confirmation is designed on specific methods An apparatus for estimation of optical properties is implemented, measurements are taken for skin substitution.

Based on a given frequency, different skin depths are thermally affected. So, superficial variable (epidermis) and subcutaneous property (dermis) can be identified with interfer observations.

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