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Nonablative Laser Skin Resurfacing of Fine and Coarse Wrinkles – Two Study Cases

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ABSTRACT

The use of the Nd^+ and Er^+: YAG lasers is still under development for cutaneous resurfacing. Cooling the epidermis induces laser heating under invasive epidermal layer regime. Injuring the dermis can treat skin defects and improve its quality. Various therapeutic options have been utilized to treat aging signs. Laser resurfacing has proven effectiveness and popularity due to its shorter recovery time and high success rate. Non-invasive Nd: YAG laser and 2940nm Er: YAG laser pulses were employed to provide deep dermal laser heating and induce elastin and collagen regeneration. Two subjects of skin-tone 2 were laser treated in the present study. Photographs were taken before the treatment and after the last session. The 1064nm Nd: YAG and 2940nm lasers treatment results were followed up in treating fine and coarse wrinkles. The patients were given four sessions every other week. The laser energy was calculated at all interfaces between the layers of the skin in order to find out the exact laser fluence, and then the temperature rise at the targeted tissue. The 1064nm Nd: YAG laser was benefited more by younger subject while the 2940nm was better for older case.

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1. Introduction

Cutaneous indicators such as wrinkles and skin laxity are commonly associated with aging skin. The most concerning location for wrinkles is on the face due to its susceptibility to wrinkling and its impact on cosmetic appearance [1, 2]. To combat these signs of aging, various therapeutic options have been utilized such as chemical peels, fillers, laser treatments, and surgery. Among these treatments, laser ablation has recently gained popularity due to its shorter recovery time and high success rate. There are two types of laser ablation: ablative and non-ablative. Despite the more effective ablative method, it is associated with longer recovery time and a higher risk of pigmentation and complications [3]. It has been discovered that photo-bio-modulation, which uses low-energy laser radiation or light-emitting diodes, improves skin laxity and minimizes wrinkles [4]. Infrared laser light has been used by numerous researchers without the need for invasive treatments. This process, which entails freezing

the epidermis, is believed to enhance skin quality by allowing heat-induced dermal injury brought on by laser radiation energy without ablation [5].

Nd: YAG laser has lower level of absorption by water than the Er: YAG laser. This benefits the benefit of using the Nd: YAG laser limited to fine line wrinkles. Contrarily, Er: YAG laser emits its photons at 2940-nm which is very close to the peak absorption of water (the targeted chromophore). This makes its efficacy of treating coarse wrinkles higher than the Nd: YAG laser. In addition, Er: YAG laser is much safer than the uses of CO_2 laser in treating wrinkles since it has an absorption coefficient 16 times greater and this decreases the penetration depth into the epidermis by a factor of ten. Many researchers have looked into and focused on the use of YAG laser radiation in this field, where long-pulse Nd: YAG laser radiations target melanin less successfully, making treatment safer for patients with all skin types [6]. Nonablative resurfacing procedures are a promising option for patients looking for less invasive, renewing therapies for their aged faces, according to research on the efficacy of employing 2940nm Er: YAG laser radiation to rejuvenate aging facial skin [7]. Non-invasive millisecond Nd: YAG laser and 2940nm Er: YAG laser pulses can provide laser heating deep in the dermis; to result in elastin and collagen regeneration. Laser parameters are chosen according to the optical characteristics of the skin [8, 9]. The outer epidermis is considered as the top layer absorber; due to the presence of melanin, while the absorption of the second, the dermis, is dominated by the water content of the cells. The laser light interacts with the tissue in four successive phases: laser light transport inside tissue, laser-induced heating within skin, localized increase of temperature in the spotted skin and heat dissipation to the outside of the targeted tissue [10, 11].

The skin's optics can be thought of as a cloudy substance that contains specific absorbers such as collagen, blood, bilirubin, and melanin. The laser fluence (J/cm^2) at the intended area determines whether there will be thermal or photochemical reactions [12, 13]. As the laser photons pass through the skin surface, they suffer from several scattering and absorption processes. The number of photons that are absorbed or dispersed varies depending on the laser wavelength, while the laser intensity of their interaction is influenced by the thermal properties of the skin and the specific parameters of the laser, such as pulse duration, spot size, wavelength, and laser fluence [3, 14].

In laser cosmetology, noninvasive lasers are used because of their limited damage as compared to ablative lasers. Laser heating effect tis used to remove aged skin and tighten it by producing new collagen and stimulate the surrounding tissues to recover naturally [15]. Although most of the non-ablative lasers used in skin rejuvenation are long pulses, the use of ultra-short picosecond laser pulses have been reported a successful outcome to clear wrinkles [16]. Higher rates of adverse events were compared between nonablative and ablative therapies. The authors suggested in their review that ablative scheme is safer and more effective than non-ablative laser modality for skin resurfacing [10]. This however opposes the conclusion of most authors who found that non-ablative laser resurfacing technique is the safer choice.

In the present work, the main novelty is the pre-calculation of laser fluence needed to reach the temperature rise needed to improve the wrinkle appearance. The pre-calculations required tracing the laser beam at every interface between the layers of the skin (five layers in the epidermis and two layers in the dermis).

At each interface a part of the incident laser beam is reflected, and the rest is transmitted. The transmitted part is again partially absorbed, scattered and transmitted to the next interface. By this way, the exact laser energy at the depth under the skin surface is worked out and used to calculate the temperature rise at the targeted tissue. Doing so will expel any laser energy overdose and ensure safe treatments without lateral damage. This was achieved by efficiently cooling the skin layers which absorbed some of the laser energy before reaching the targeted tissue.

2. Theoretical Part

For laser radiation treatments, the wavelength and pulse width of the laser radiation light are essential characteristics. Positive therapeutic outcomes are anticipated if we can find out these parameters for laser radiation. The heated tissue is a function of the laser intensity, pulse duration and the tissue optical parameters. The heat propagation, on the other hand, is governed by the tissue thermal conductivity and diffusivity, as well as the interaction time [17]. In the present study, the calculation required a previous knowledge of the depth of the

targeted tissue and the skin-tone (function of melanin quantity) [18]. These two parameters influence directly the Lambert law as expressed in Eq. (1) hereunder. The present work adopts a new method, where the laser dose is pre-calculated to ensure perfect results without side effects.

$$I(\chi) = I_o \; exp.(-\mu_a \, \chi) \quad (1)$$

Where:
$I(\chi)$: The intensity at distance χ from the skin surface (w/cm²)
I_o: The incident intensity (w/cm²)
χ: The laser penetrated depth under the skin surface (mm)
μ_a: The absorption coefficient of the skin dermis or epidermis (cm^{-1})

The absorption coefficient depends on absorbing chromophore and laser wavelength [19]. The epidermal absorption coefficient μ_e includes the absorption of both melanin and baseline skin. It is given in Eq. (2):

$$\mu_e = melanin\ \%\ x\mu_1 + (1 - melanin\ \%)\ x\mu_2 \quad (2)$$

Where:
μ_e: absorption coefficient of epidermis (cm^{-1})
Melanin %: melanosomes content per unit volume
μ_1: absorption coefficient of melanin (cm^{-1})
μ_2: absorption coefficient of skin baseline (cm^{-1})

Two crucial skin-related variables were needed for the current computations: the target location (depth) and skin phototype (melanin concentration). The Lambert law is directly impacted by these two variables [18]. Table 1 shows that the component pertaining to dermal and epidermal thickness was extracted straight.

Table 1: Skin thickness [18, 20, 21].

Skin location	Thickness (micrometer)
Upper medial forehead	44
Lower medial forehead	45
Upper lateral forehead	44
Lower lateral forehead	39

The melanosomes per unit volume for light skin is ≈1.3-6.3%. The epidermal baseline and melanin absorption coefficient for low (4% volume) melanin concentration skin at 1064nm = 3.19 cm^{-1}. The overall dermal coefficient of absorption; μa (der) depends on the absorption of water and hemoglobin, but weakly on the absorption of baseline skin [18, 20]. The fraction volumes of water and blood (%), and the wavelength of laser light (nm) are utilized to find the μa (der) in cm^{-1}. The absorption of dermal and epidermal baseline absorption is similar and are referred as μ_2. For even distribution of blood and water and blood in the skin, the dermal coefficient of absorption is:

$$\mu_a\ (dermis) = blood\ \%\ \mu_a\ (blood) + water\ \%\ \mu_a\ (water) \quad (3)$$

For Eq. (3) when using the Er: YAG (2940nm) laser, the water content is the absorbing chromophore; making the parameters of blood going to null [22]. The absorption peak of this laser is very close to the peak absorption of water (3000nm), and there will be no absorption by melanin as shown in Fig. 1.

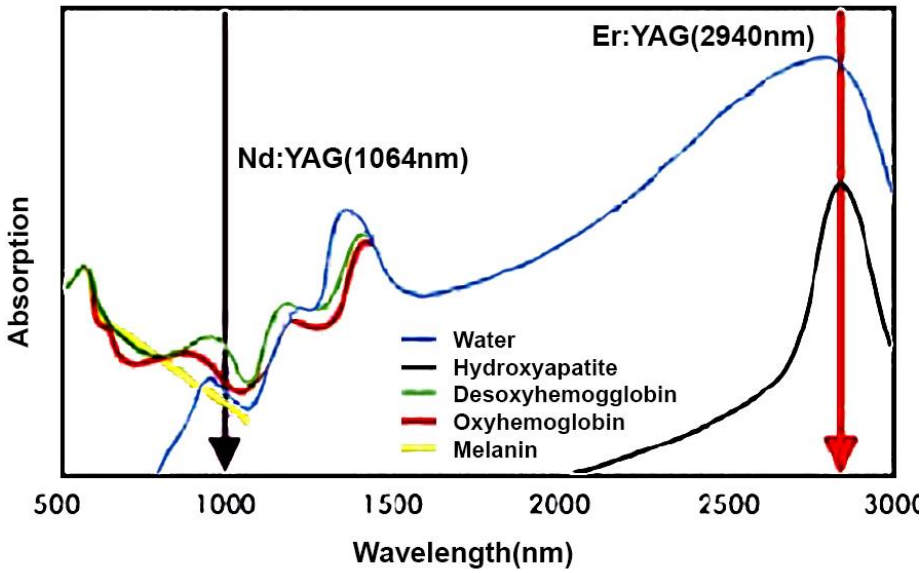

Figure 1: Light absorption of main skin chromophores [19].

The pure water absorption coefficient at the laser wavelength 2940nm is around13000 cm^{-1} [18, 23, 24]. Table 2 quotes some data from a published article elsewhere.

Table 2: Some data from literature [18].

Wavelengths (nm)	μ_a (cm^{-1})	μ_d (cm^{-1})	μ_t (cm^{-1})
1046 (light skin)	3.19	2.9	133
2940 (light skin)	-	2400	-

The Nd: YAG laser has an absorption coefficient in the melamine layer, and this is considered as an energy loss element for the laser beam reaching the dermis layer. Besides; this laser wavelength has a scattering coefficient in both the epidermis layer and the dermis [25]. This is considered as attenuation in the epidermis layer, but in the dermis, it increases the absorbed laser energy. After taking into account these factors, the laser energy needed to produce the exact safe results with high accuracy and no side effects can be per-calculated [3]. Er:YAG laser, is distinguished by its high absorption in water, which significantly influences its superficial penetration depth in skin tissues. Due to this high absorption, the Er laser is predominantly absorbed within the uppermost layers of the skin, primarily the with minimal penetration into deeper layers. The laser energy is rapidly converted into thermal energy upon absorption. This limited penetration depth is advantageous for procedures aimed at treating superficial skin conditions and reducing the risk of damage to deeper dermal structures. The ability to confine the thermal effect to the surface layers allows for effective skin resurfacing with improved safety and recovery profiles.

3. Devices and Techniques

In the current study, Clint's respect was necessary. They were a mid-age male was invited twice to the laser aesthetic center to explain the procedure we intended to follow. They were informed about the benefits and risks of laser treatment. For their best interest, they were given the right to withdraw from the laser therapy sessions if they were not convinced with the information about the results and risks involved and the alternative treatment methods available. Expected risks against benefits of the laser procedure were thoroughly explained to let them know how the treatment is going to affect her quality of life. they finally agreed to take the treatment and signed the consent to cooperate in collecting the data during the follow-up time. This study adhered to the principles of the Declaration of Helsinki and received ethical approval from the Institutional Review Board (IRB). The Department of Applied Sciences at the University of Technology-Iraq granted approval to conduct this study, with the approval number [A.S-L.S.T 4643 on 6/11/2022]. Informed consent was obtained from all individual participants included in the study, ensuring their anonymity and confidentiality.

The subjects received treatment every other week on the forehead: one subject with Er: YAG laser and the other with long pulse Nd: YAG laser. The resurfacing device used was Er: YAG - ACTION II™ (2940 nm) in noninvasive skin tightening, from Lutronic intelligent care, Billerica, while the one that provides long Nd: YAG laser pulses was (Elite + TM Cynosure, Westford, Massachusetts, United State). The selected laser parameters and skin conditions are shown in table 3.

Table 3: Laser parameters and skin conditions.

Subject	Age	Skin tone	Region	Spot diameter (mm)	Fluence (J/cm^2)	Pulse duration (ms)	Rep. rate (Hz)	Temperature after cooling (°C)
1	33	2	forehead	5	20	25	1	4
1	60	2	forehead	16	5	100	1	4

The treatment was made in three passes: on the targeted skin with parallel cooling. Optimum laser settings (doses) were based on our pre-calculations to induce mild erythema on the forehead. Laser thermometer and DESS skin phototype analyzer (model GB531) were utilized to recognize the skin temperature and color. Table 4 summarizes some experimental data for the two lasers used.

Table 4: Experimental data for the two lasers used.

Subject	Laser Wavelength (nm)	Skin Color	Fluence Before Reflection (J/cm^2)	Fluence After Reflection (J/cm^2)	Epidermal Temperature	Depth of Dermal Temperature °C		
						1mm	2mm	3mm
1	1064	2	20	18.6	41	44	43	41
2	2940	2	5	4.6	23	80	----	----

Aesthetic laser applications are based on laser –tissue interaction in which the laser beam is considered point and line heating sources. The human skin consists mainly of three regions: epidermis, dermis and hypodermis as shown in Fig. 2. Every sub-layer has its own properties, structure and function and it absorbs, scatters and transmits a certain amount of the incident laser beam.

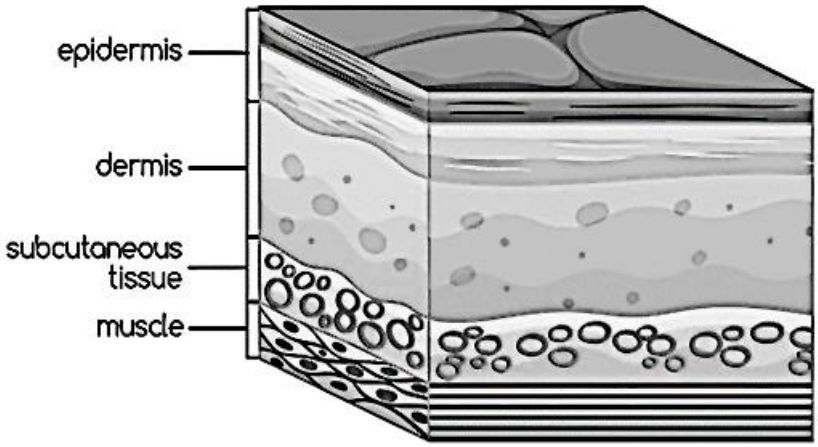

Figure 2: Human skin layers [17].

4. Treatment Protocol

Many researchers are working on the physics of laser interaction with skin layers and attempt to develop a suitable scenario. Being aware of the mechanisms and the limitations can help provide the laser therapy and reduce collateral damage [18-20]. The essential factors needed to consider in this process include pulse length, absorbed wavelength for a specific target, heat relaxation time, and the concept of energy balance (also known as the conservation of energy) [26]. Once these factors are found, the laser fluence below the surface can be determined. By accurately substituting the coefficients of scattering and absorption, the laser dose at the skin surface, the target

dimensions and the pulse length, it becomes feasible to estimate the temperature rise needed by the targeted tissue, as given in Eq. (4).

$$\Delta T = [F\mu/c\rho][t/(t+\tau)]1/g \quad (4)$$

Where F is the laser fluence of local subsurface, ρ is the skin structure density, c is the specific heat "g" is constant = 3 for spheres, 2 for cylinders, and 1 for planes, τ is the laser pulse duration, and t is the targeted tissue heat relaxation time ≈ 4 ms for the dermal layer [26]. The flow chart was designed to follow the beam physically and precisely determine the parameter (Fig. 3).

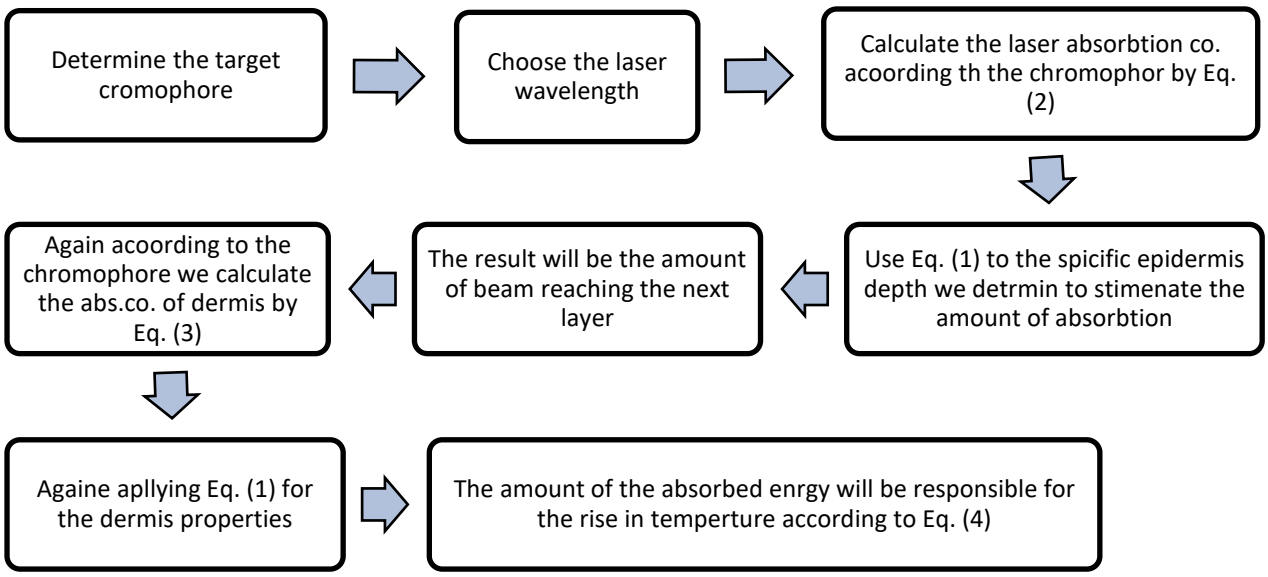

Figure 3: Flow chart of the physical calculation.

A mild skin cleaner was used to clean the face prior to the treatment. The skin of both patients was chilled in advance to a temperature of 3 °C. The patients wore goggles for eye protection during the laser therapy. The targeted forehead was treated with its laser recipe. Following the procedure, zinc oxide ointment was applied to the treated region, and patients received instructions regarding sun protection and post-laser therapy maintenance. Two monthly therapy sessions were assigned to each patient, one with long pulse Nd: YAG laser and the other with long pulse Er: YAG laser. For examination and recording of side effects, patients came back one week following each treatment session. Records were kept of the downtimes following the laser surgeries. After the laser treatment, the downtime indicates how long the potential erythema or edema on the face lasted to go away. Camera-captured images were acquired prior to each treatment session and two months following the last treatment.

5. Results and Discussion

Overall clinical improvement was equal for both Nd: YAG and Er: YAG treated subjects with an average improvement in 70% Fig. 3 and 4. Faster healing was observed on the long pulse Er: YAG treated case. Decreased erythema and less edema were observed on the Nd: YAG treatment case [6].

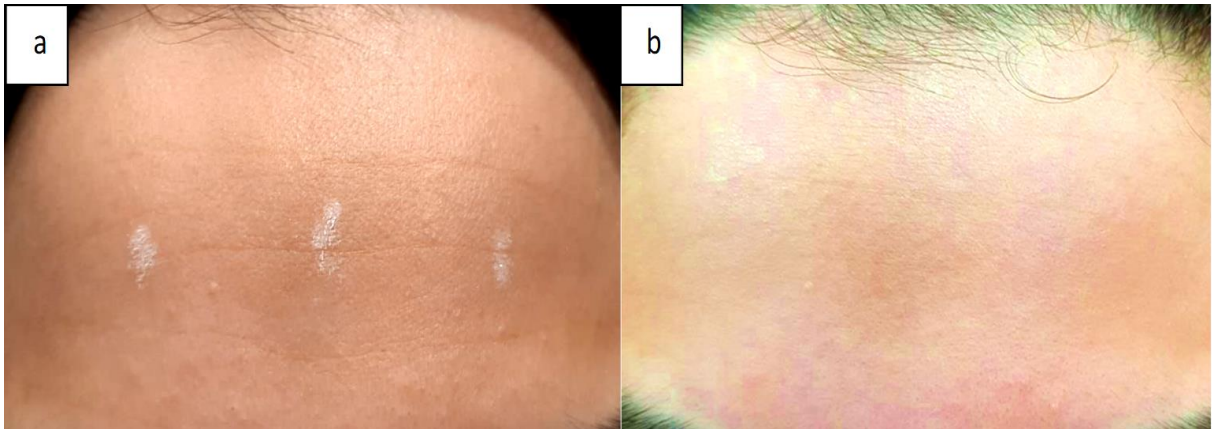

Figure 4: The fine lines (a) before and (b) 2 months after the 1064nm laser

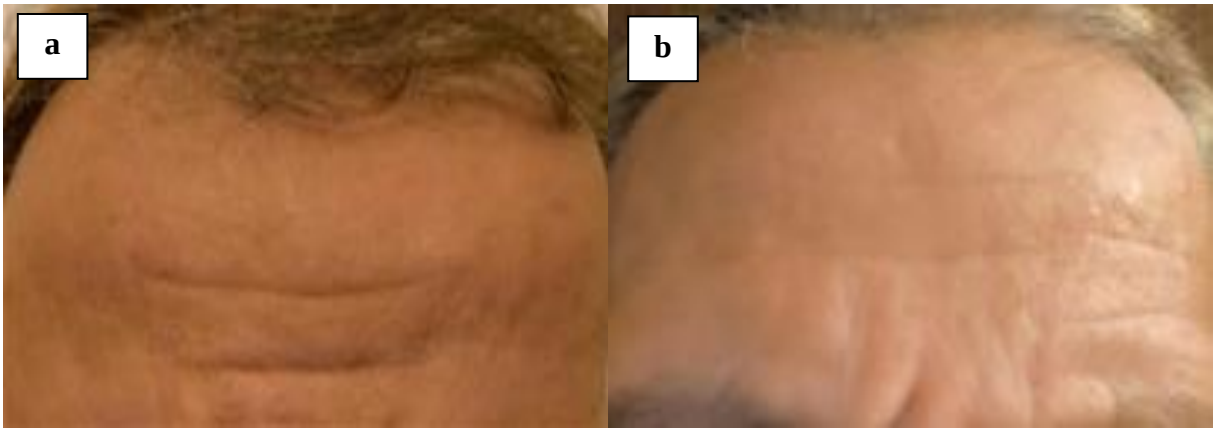

Figure 5: Coarse wrinkle treatment with 2940nm Er: YAG laser; (a) before and (b) after 3 sessions of laser treatment

Due to its remarkable ability to absorb MIR light in water, the Erbium: YAG laser wavelength is the optimal choice for minimizing thermal damage to underlying tissue. The typical residual thermal damage (RTD) is limited to a depth of only 20-50 μm; making it the preferred option for faster skin re-epithelialization compared to lasers with deeper penetration. The present study included an in vivo human model to demonstrate the remarkable ability of rapid Er: YAG laser pulse stacking to coagulate deep collagen while avoiding complete epidermal ablation. We observed a deepening of the thermally impacted zone and a non-linear increase in surface temperature over time because of the laser pulse. This effect was more significant when compared to shorter pulse durations and led to a reduction in peak surface temperature. Interestingly, a previous model of using Er: YAG had predicted this same outcome on human skin [14], and agrees well to the histologic observation of our most recent in vivo study [25]. In our most recent in vivo examination [21], we observed that laser skin irradiation [4, 27] harmonizes well with histological findings. Moreover, nonablative YAG laser resurfacing has proven to be a highly effective and low-risk option, providing patients with subtle, yet noticeable improvements in their skin. By avoiding damage to melanin chromophores, the 1064-nm neodymium laser enables deeper energy penetration into dermis Fig. 6.

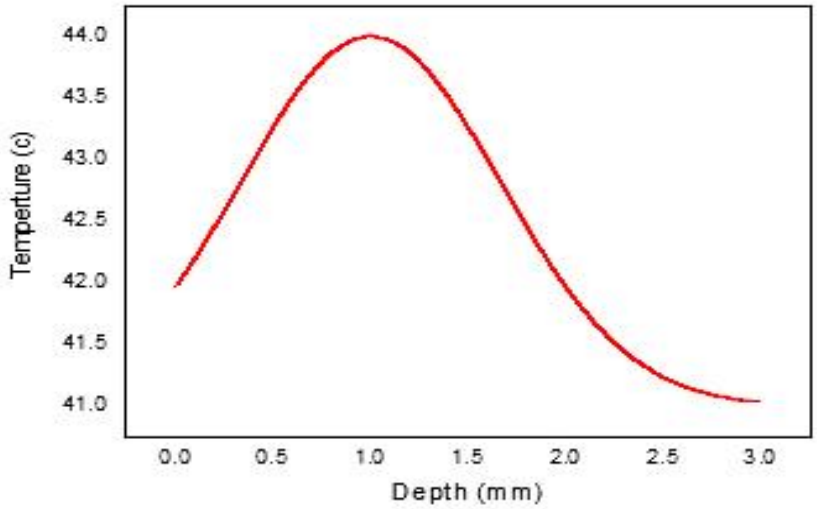

Figure 6: The rise in temperature along the path of 1064 nm.

This curve shows the rise in temperature just below the surface, which is consistent with recent literature that has explained this phenomenon as being caused by scattering within the surface in the dermal tissue [10].

The laser penetration depth and temperature rise relationship between skin layers is crucial for understanding laser-based medical treatments and dermatological procedures. As a laser beam interacts with the skin, its penetration depth is governed by the wavelength of the laser and the optical properties of the skin, such as absorption and scattering coefficients. Shorter wavelengths, typically used in applications like laser resurfacing, are absorbed predominantly in the epidermis, leading to localized heating and potential damage in this outer layer. Conversely, longer wavelengths penetrate deeper into the dermis, where they can induce significant thermal effects and stimulate collagen remodeling. The temperature rise within the skin layers is influenced by the energy density of the laser and the thermal conductivity of the skin, with greater temperature increases occurring at higher laser intensities or shorter pulse duration. This localized heating can trigger therapeutic responses, such as increased collagen production, but also necessitates precise control to avoid adverse effects like burns [26].

To further protect the epidermis from potential thermal harm, both lasers have built-in skin-cooling mechanisms. This means that individuals of all skin types can safely undergo laser treatment when employing the long-pulse 1064-nm Nd: YAG laser. Furthermore, patients treated with this laser showed significant improvements in skin texture and wrinkles [1]. Despite varying skin types, none of the patients experienced blisters, long-lasting redness, scarring, or loss of pigmentation. Our patients did not report any significant negative reactions following treatment. The assessment of anesthesia requirements for each patient was overwhelmingly positive. Initially, our use of this laser resulted in high levels of satisfaction among patients, as indicated in the treatment evaluation forms. Patients were pleased with the short period of the treatment (only a few minutes), the noticeable improvement in their skin, and the convenience of receiving treatment at our office. After the initial treatment, the subjects did not see apparent changes change. However, week 6, after the third session, the subjects started to experience a noticeable improvement in the texture of their skin. By the time they had completed their fourth treatment, patients were pleased to see a significant difference in the overall appearance of their skin, which continued throughout the remaining treatment sessions.

6. Conclusions

Non-invasive Nd: YAG laser and 2940nm Er: YAG laser pulses resulted in short recovery time and very limited side effects in the treatment of fine and coarse wrinkles. Pre-calculated exact laser fluence and therefore, temperature rise calculations allowed very efficient laser treatments with short recovery times. The results confirm the relevancy of using the 1064nm Nd: YAG laser for fin-lines wrinkles and the 2940nm for the deep coarse wrinkles. No side effects were seen, and only a limited number of treatments was required.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

[1] C. Raulin and W. Kimmig, "Laser therapy in dermatology and aesthetic medicine: side effects, complications, and treatment errors," *Energy Ski. Eff. Side-Effects Lasers, Flash Lamps Other Sources Energy*, pp. 13–25, 2022.

[2] G. I. Sharipova, "Light and laser radiation in medicine," *Eur. J. Mod. Med. Pract.*, vol. 2, no. 1, pp. 36–41, 2022.

[3] M. B. Mustafa, W. K. Hamoudi, and K. S. Khashan, "Optimized selection of neodymium laser parameters for successful enlarged veins treatment," *Lasers Med. Sci.*, vol. 38, no. 1, p. 264, 2023.

[4] L. Hoffman, E. Smeallie, N. Ugonabo, and A. Chapas, "Neck and chest rejuvenation with fractional 1440 and 1927-nm low-powered diode laser," *Lasers Surg. Med.*, vol. 56, no. 3, pp. 233–238, 2024.

[5] W. Selting, "Laser operating parameters for hard and soft tissue, surgical and PBM management," in *Lasers in Dentistry—Current Concepts*, Springer, 2024, pp. 65–96.

[6] N. Sari, F. Salim, M. Sara, E. W. Fitri, and M. Bulqiah, "Efficacy of 1064nm neodymium-doped yttrium aluminum garnet (Nd: YAG) laser and 2940nm fractional erbium laser for severe acne with acne scar: a case report," *Bali Med. J.*, vol. 12, no. 2, pp. 1676–1679, 2023.

[7] T. M. Hammoda, N. A. Ahmed, and M. Hamdino, "Fractional CO_2 laser versus 1064-nm long-pulsed Nd: YAG laser for inflammatory acne vulgaris treatment: a randomized clinical trial," *Lasers Med. Sci.*, vol. 38, no. 1, p. 187, 2023.

[8] M. M. Kim and A. Darafsheh, "Light sources and dosimetry techniques for photodynamic therapy," *Photochem. Photobiol.*, vol. 96, no. 2, pp. 280–294, 2020.

[9] W. Hamoudi, "Laser-Human Skin Interaction: Analytical Study and Optimization of Present Non-Ablative Laser Resurfacing," *Iraqi J. Appl. Phys.*, vol. 4, no. 3, 2008.

[10] H. N. Mirza, F. N. Mirza, and K. A. Khatri, "Outcomes and adverse effects of ablative vs nonablative lasers for skin resurfacing: a systematic review of 1093 patients," *Dermatol. Ther.*, vol. 34, no. 1, p. e14432, 2021.

[11] M. B. Mustafa, W. K. Hamoudi, and H. H. Maqdasi, "Temperature rise control for safe treatment of varicose vein by Nd: YAG laser," in *AIP Conference Proceedings*, AIP Publishing, 2021.

[12] W. K. Hamoudi, Q. K. Alhashimi, M. B. Mustafa, and N. R. Abdulhameed, "Pre-calculated relevant Nd: YAG laser parameters for optimized varicose veins treatment," in *Journal of Physics: Conference Series*, IOP Publishing, 2021, p. 12053.

[13] P. L. Bencini and S. Guida, "Skin Resurfacing: Ablative and Non-ablative Lasers," *Technol. Pract. Dermatology Non-Invasive Imaging, Lasers Ulcer Manag.*, pp. 357–367, 2020.

[14] N. A. Shanina, A. V Patrushev, and A. Zorman, "Histological and immunohistochemical changes in facial skin treated with combined ablative and non-ablative laser therapy," *J. Cosmet. Dermatol.*, vol. 20, no. 11, pp. 3509–3516, 2021.

[15] N. N. Houreld, "The use of lasers and light sources in skin rejuvenation," *Clin. Dermatol.*, vol. 37, no. 4, pp. 358–364, 2019.

[16] P. H. Wardhani, C. R. S. Prakoeswa, and M. Y. Listiawan, "Evaluation of Wrinkle and Dermal Thickness in the Forearm before and after Picosecond Laser Therapy," *J. Cutan. Aesthet. Surg.*, vol. 17, no. 1, pp. 7–10, 2024.

[17] E. L. Tanzi, J. R. Lupton, and T. S. Alster, "Lasers in dermatology: four decades of progress," *J. Am. Acad. Dermatol.*, vol. 49, no. 1, pp. 1–34, 2003.

[18] M. H. Niemz, "Laser-Tissue Interactions." Springer-Verlag, 2007.

[19] M. S. Brown and C. B. Arnold, "Fundamentals of laser-material interaction and application to multiscale surface modification," in *Laser precision microfabrication*, Springer, 2010, pp. 91–120.

[20] M. Boord, "Laser in dermatology," *Clin. Tech. Small Anim. Pract.*, vol. 21, no. 3, pp. 145–149, 2006.

[21] A. J. Welch, J. H. Torres, and W.-F. Cheong, "Laser physics and laser-tissue interaction," *Texas Hear. Inst. J.*, vol. 16, no. 3, p. 141, 1989.

[22] M. A. Ansari and E. Mohajerani, "Mechanisms of laser-tissue interaction: I. optical properties of tissue," 2011.

[23] D. A. O. Modena, A. C. G. Miranda, C. Grecco, R. E. Liebano, R. C. T. Cordeiro, and R. M. Guidi, "Efficacy, safety, and guidelines of application of the fractional ablative laser erbium YAG 2940 nm and non-ablative laser erbium glass in rejuvenation, skin spots, and acne in different skin phototypes: a systematic review," *Lasers Med. Sci.*, vol. 35, no. 9, pp. 1877–1888, 2020.
[24] S. Jacques and M. Patterson, "Light–tissue interactions," in *Handbook of Laser Technology and Applications*, CRC Press, 2021, pp. 201–225.
[25] A. Badawi, T. Sobeih, and V. Jasmina, "Periocular rejuvenation using a unique non-ablative long-pulse 2940 nm Er: YAG laser," *Lasers Med. Sci.*, vol. 37, no. 2, pp. 1111–1118, 2022.
[26] K. Nouri, *Lasers in dermatology and medicine: dermatologic applications*. Springer, 2018.
[27] R. Dai, X. Yang, Y. Su, and X. Wu, "Effectiveness and safety of the ablative fractional 2940-nm Er: YAG laser for the treatment of androgenetic alopecia," *Lasers Med. Sci.*, vol. 39, no. 1, pp. 1–9, 2024.