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Transformative Role of Laser Technology in Ophthalmology and Dermatology: A Mini Review of Precision Applications in Modern Medicine

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REVIEW

Transformative Role of Laser Technology in Ophthalmology and Dermatology: A Mini Review of Precision Applications in Modern Medicine

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ABSTRACT

Laser technology has significantly transformed healthcare and biological sciences by Laser devices are offered precision, efficiency, and Multiple simple solutions in various medical fields and research domains. In ophthalmology, lasers play a pivotal role in vision correction, retinal imaging, and therapeutic applications, such as femtosecond laser-assisted LASIK and two-photon fluorescence scanning laser ophthalmoscopy. Dermatology has also benefited from CO_2, Nd:YAG, excimer, and Q-switched lasers, which are widely used for pigmentation disorders, tattoo removal, and skin rejuvenation. Moreover, Low-Level Laser Therapy (LLLT) enhances wound healing and tissue regeneration, while intense pulsed light (IPL) and diode lasers improve hair removal and acne treatments. Furthermore, laser applications are rapidly advancing across fields such as surgical oncology, neurology, and regenerative medicine, with promising roles in gene therapy, optical coherence tomography (OCT), and photodynamic therapy (PDT). Despite these advancements, challenges such as safety concerns, laser-induced complications, and the need for further clinical validation in diverse patient populations. This paper explores cutting-edge laser applications in ophthalmology, dermatology, and beyond, highlighting their transformative impact on modern medicine and future potential for innovation.

Keywords: Refractive errors, Ophthalmology, Dermatology, Nd:YAG laser, CO_2 laser

1. Introduction

Laser technology has revolutionized various fields of biology and medicine [1], providing precise, minimally invasive, and highly effective solutions for both diagnostic [2], and therapeutic applications [3]. With its unique properties—monochromaticity, coherence, directionality, and high intensity—laser technology has become an indispensable tool in modern healthcare, for example in smart contact lenses (CLs) fabrication [4]. Beyond traditional healthcare applications, lasers are also revolutionizing medical communication and data transmission. Recent research by Al-Hadhrami et al. (2024) introduced a prototype laser communication system using uncrewed aerial vehicles (UAVs) as relay points to enhance data connectivity in remote healthcare applications [5]. This system overcomes the range and reliability limitations of conventional radio frequency (RF) communication, offering high-speed, real-time data transmission with improved integrity. Lasers were widely adopted in ophthalmology for vision

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correction procedures, such as excimer laser surgery, femtosecond laser (Femto), and femto-LASIK, which have proven to be highly effective in reshaping the cornea and restoring clear vision. These methods provide precision, rapid recovery, and long-term stability, making them the preferred choice for correcting refractive errors. More recently, advancements in ophthalmic imaging have expanded laser applications beyond vision correction. The study by Boguslawski et al. (2022) explores the use of 2-Photon-Excited Fluorescence Scanning Laser Ophthalmoscope (TPEF-SLO) for noninvasive, in vivo imaging of the human retina, allowing for early disease detection [6]. Findings demonstrate that TPEF-SLO can image and quantify visual cycle intermediates and metabolic byproducts, providing high-resolution imaging with minimal laser power, ensuring safety for human use. These technological advancements in laser-based ophthalmology illustrate the transformative role of lasers, offering both corrective and diagnostic solutions for improved eye health and vision care.

Beyond ophthalmology, dermatology has also benefited from laser advancements [7]. Laser therapy is extensively used to treat various skin conditions, working by directing a highly concentrated beam of light to a targeted area. This energy is absorbed by specific pigments or skin structures [8], enabling the controlled removal or modification of tissues without damaging surrounding healthy cells [9]. The field continues to expand, with newer laser-based applications such as vascular lasers, excimer lasers, low-level laser therapy (LLLT) [10], laser lipolysis [11], and laser-assisted drug delivery [12], enhancing safety [13], efficacy, and precision in dermatological treatments.

However, the impact of laser technology extends far beyond ophthalmology and dermatology. Modern innovations have expanded laser applications into various medical and biological disciplines as shown in Fig. 1. In surgery, lasers facilitate tumor excision with minimal damage [14], and enable lithotripsy for kidney stones via Holmium:YAG lasers [15]. Dentistry benefits from laser-assisted cavity treatment and gum surgeries, improving disinfection and reducing pain [16]. In neurology, Laser Interstitial Thermal Therapy (LITT) provides a minimally invasive approach for brain tumor ablation with real-time MRI guidance [17]. Orthopedics utilizes LLLT to promote bone regeneration and reduce inflammation in osteoarthritis and post-surgical recovery [18]. Oncology leverages Photodynamic Therapy (PDT) and laser-induced hyperthermia for selective cancer cell destruction [19]. In gynecology, Laser-Assisted Hatching (LAH) improves in vitro fertilization (IVF) implantation success rates [20]. Optical Coherence Tomography (OCT) enables high-resolution imaging for ophthalmology and cardiovascular diagnostics, detecting early signs of diabetic retinopathy and atherosclerosis [21]. In genetics, laser microdissection and gene transfection technologies have advanced targeted cancer gene therapy [22].

These applications demonstrate the transformative role of laser technology in medicine and biology, providing precision, efficiency, and minimally invasive solutions. As research continues, further advancements in laser-based therapies, imaging techniques, and personalized medicine will enhance patient outcomes and open new frontiers in medical science.

2. Lasers used in correcting refractive errors: Case studies

The reduction in visual acuity comes from the error in light rays focusing by the refractive imaging system of the eye (cornea, iris, the crystalline lens and the retina) called a refractive error [23], as well as those related to CLs wearing [24]. Refractive errors come in two main parts spherical (Myopia and Hyperopia) and cylindrical errors [25].Visual acuity performance diminishes whenever any of the contributing functions have not been optimized. Most CLs are prescribed for cosmetic purposes and many patients use them in sport activities. Refractive errors can be corrected by glasses, CLs or LASIK surgery (implementing of intraocular lens IOL and laser surgery) [26]. Patients with very high refractive errors (severe myopia, hyperopia, or astigmatism) often prefer to use CLs, they are much more comfortable than wearing heavy thick spectacle lenses.

The provided box plot illustrates the RMS (Root Mean Square) aberration coefficients for patients with Post-LASIK ectasia, comparing values before and after scleral lens usage as described by Kumar et al. 2021 [27]. The data show a reduction in higher-order aberrations (HO-RMS), coma, secondary astigmatism, and trefoil distortions after CL application, suggesting that CLs help mitigate post-surgical visual distortions. Additionally, the surgery is sometimes not suitable for all age groups, leading many visually impaired individuals to rely on CLs, which have been in use for over 125 years to reduce distortions, refractive errors, or astigmatism [28]. As shown in the post-LASIK ectasia study, CLs effectively minimize higher-order aberrations [29], providing a better alternative for individuals who cannot undergo LASIK. CLs offer enhanced durability in various environmental conditions, making them ideal for daily and monthly wear [30], antibacterial activity [31], biological activities monitoring [32], etc.

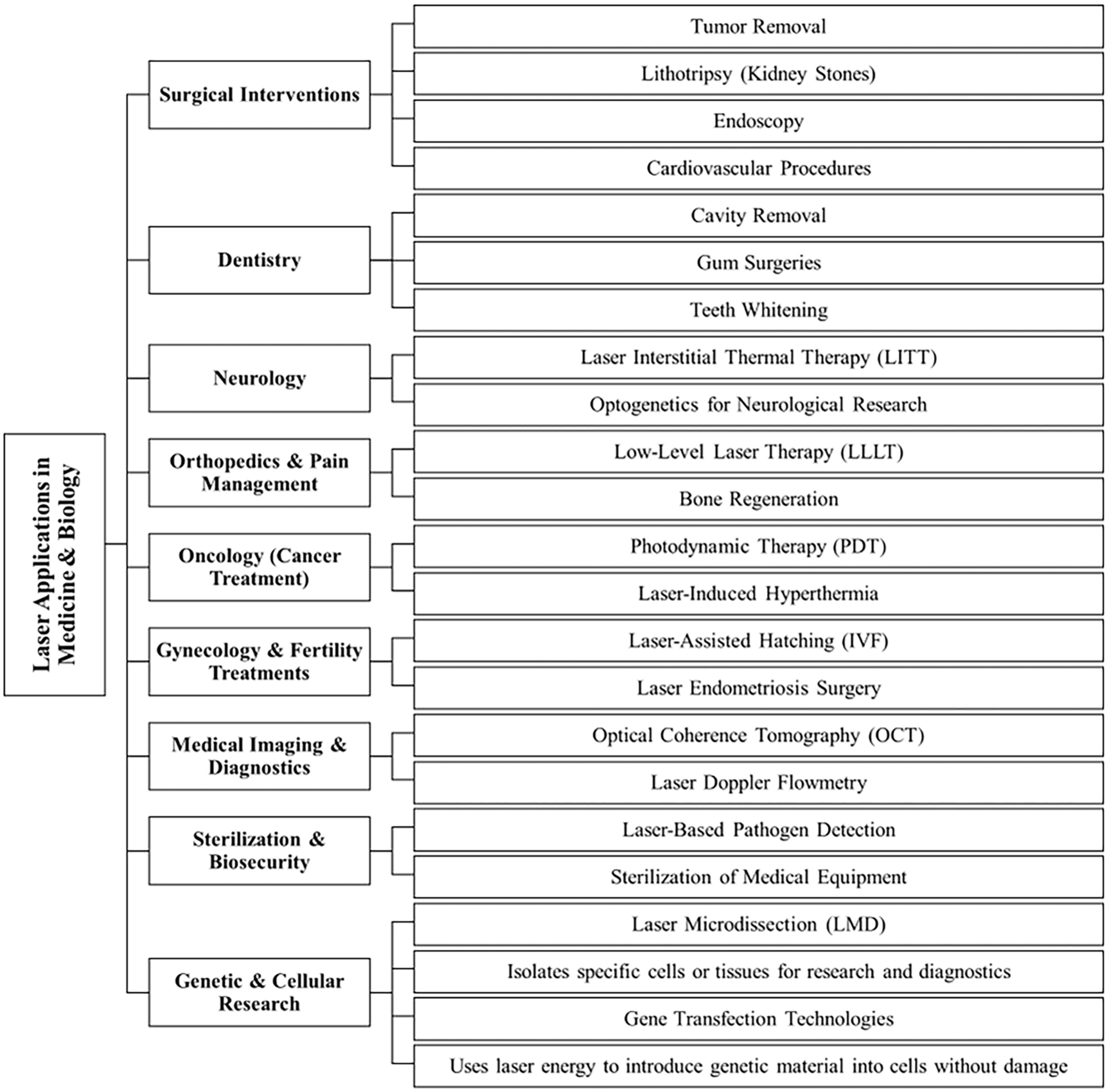

Fig. 1. Key applications of laser technology in medicine and biological research.

Laser-based optical technologies have advanced significantly in recent years, enabling breakthroughs in fields such as ophthalmology, infrared imaging, and computational laser modeling. These technologies leverage femtosecond (fs) lasers, Nd:YAG lasers, excimer lasers, and solid-state UV lasers to improve surgical precision, enhance imaging performance, and optimize computational models for biomedical applications. Recent advancements in laser-based optical technologies have significantly improved ophthalmic surgery, infrared imaging, and computational modeling for laser-tissue interactions. Asshauer et al. (2021) demonstrated the superiority of femtosecond lasers (fs-lasers) in LASIK, SMILE, and FLACS, emphasizing their ability to minimize thermal damage and improve corneal stability [33], making them the safest and most precise option for corneal surgery [34]. Wang et al. (2023) explored a different application by leveraging fs-laser-assisted wet etching to fabricate chalcogenide glass-based infrared artificial compound eyes (IR ACE), achieving high-resolution imaging (20.16 lp mm^{-1}), a 60° field of view, and 60–70% IR transmittance, marking a breakthrough in robot vision, 3D motion tracking, and IR imaging applications [35]. Abdelhalim et al. (2023) developed a computational model for laser-cornea interaction, identifying the 213 nm Nd:YAG laser as a promising alternative to the 193 nm excimer laser while raising concerns about excessive heat generation (527.2°C) in 266 nm lasers [36]. Abdelhalim et al. (2024) introduced a 266 nm Nd:YAG flying-spot laser platform as a potential solid-state alternative to excimer lasers for hyperopic correction, demonstrating comparable ablation efficiency with lower maintenance costs but requiring further thermal optimization [37]. Finally, Zanellati et al. (2025) contributed to retinal

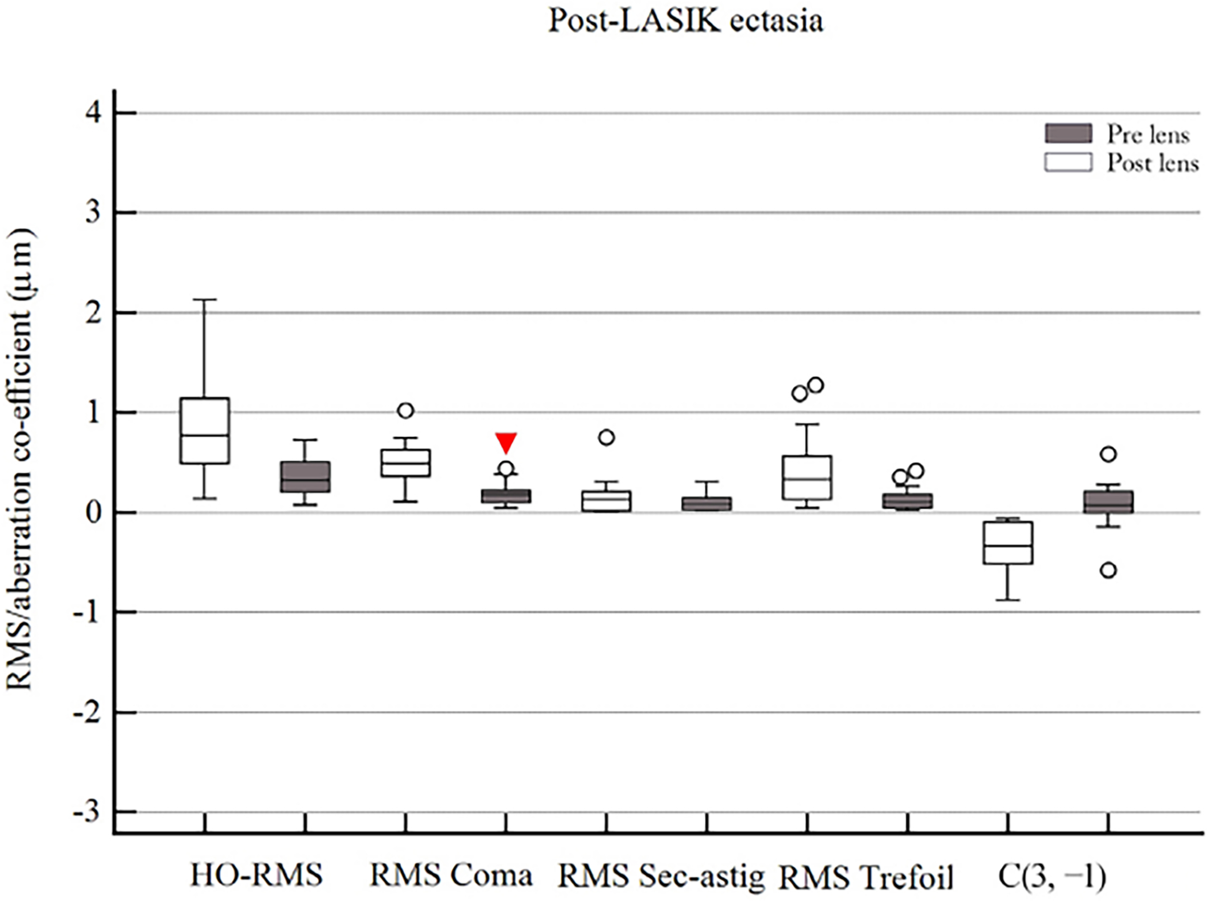

Fig. 2. Box plots showing the distribution of higher-order aberrations before and during scleral lens wear for post-LASIK ectasia.

laser therapy modeling by compiling precise optical and thermal tissue parameters, crucial for improving bioheat transfer models and ensuring safe and effective retinal laser photocoagulation [38]. While each study focuses on a distinct aspect of laser-based technology, they collectively highlight the growing role of fs-lasers, Nd:YAG alternatives, and computational models in refining surgical precision, optimizing laser safety, and expanding high-performance imaging capabilities. Future research should integrate AI-driven surgical tracking, enhanced cooling mechanisms, and patient-specific laser modeling to maximize the clinical and technological impact of these innovations.

These five studies contribute to advancing laser technology across multiple disciplines, demonstrating the versatility of fs lasers, Nd:YAG lasers, and computational modeling in medicine and imaging.

3. The use of laser in skin diseases treatments: Case studies

Laser technology is extensively used in dermatology and aesthetic medicine, offering targeted treatments for various conditions. The dye laser (595 nm) is effective in removing unwanted pigmentation by targeting pigmented skin issues through selective photothermolysis [39]. The Xenon chloride excimer laser (308 nm) is widely used in treating autoimmune skin diseases [40]; like psoriasis, vitiligo, and alopecia, promoting skin regeneration and reducing inflammation [41]. In body contouring, the lipolysis laser (1444 nm) is utilized for fat reduction, liquefying fat cells for metabolic removal or assisted liposuction [42]. Q-switched lasers (532 nm, 585 nm, 1064 nm) are applied for tattoo and hair removal, as well as skin rejuvenation, each wavelength targeting different pigments and depths to achieve optimal cosmetic results [43]. LLLT at 661 nm enhances wound healing by stimulating collagen production and blood circulation, accelerating tissue repair [44]. Additionally, the Nd:YAG laser (1064 nm) is frequently used for aesthetic skin treatments, including facial tightening, collagen stimulation, and global skin enhancement, offering deep penetration with minimal downtime [45]. Laser technology in dermatology has evolved significantly, enabling precise, effective, and minimally invasive treatments for various skin

Table 1. Comprehensive analysis provides an in-depth comparison, highlighting the significance, applications, and future potential of each study in the field of laser-based medical and imaging technologies.

Study & Year	Main Focus	Laser Technology Used	Key Findings	Advantages Over Existing Methods	Future Research Directions
Abdelhalim et al. (2024)	Flying-Spot Laser for Hyperopic Correction	Nd:YAG (266 nm) fourth-harmonic laser	Developed a flying-spot laser eye-surgery platform as a solid-state alternative to 193 nm excimer lasers, demonstrating comparable corneal reshaping efficiency while reducing maintenance requirements.	- Lower maintenance costs than excimer lasers. - External laser coupling capability increases flexibility. - Automated debris removal & cooling system enhances safety.	- Optimize cooling techniques to mitigate excessive heat generation. - Improve scanning speed to enhance precision & efficiency. - Clinical trials needed to validate long-term safety & efficacy.
Asshauer et al. (2021)	Femtosecond Lasers in Ophthalmic Surgery	Femtosecond (fs) lasers for LASIK, SMILE, FLACS	Fs-lasers provide high-precision, low-energy ablation, reducing thermal damage & recovery time in corneal and cataract surgery.	- Non-thermal laser ablation improves safety. - Higher corneal biomechanical stability than excimer-based LASIK. - Faster healing time due to minimal mechanical stress.	- Integrate AI-guided laser tracking for real-time precision enhancement. - Improve fs-laser pulse energy optimization for greater efficiency in corneal surgeries. - Expand fs-laser applications in other eye surgeries (e.g., lens replacement, glaucoma surgery).
Abdelhalim et al. (2023)	Mathematical Model for Laser-Cornea Interaction	Excimer (193 nm), Nd:YAG (213 nm, 266 nm) lasers	Identified 213 nm Nd:YAG laser as a viable alternative to excimer lasers. Found 266 nm lasers generated excessive heat (~527.2°C), making them unsuitable for clinical applications.	- 213 nm laser closely mimics 193 nm excimer laser ablation. - Eliminates reliance on toxic excimer gas-based systems. - 213 nm laser causes less thermal diffusion than excimer lasers.	- Conduct in-vivo testing of 213 nm Nd:YAG lasers to validate corneal ablation efficacy. - Develop adaptive laser pulse regulation to optimize energy levels. - Optimize delivery systems for uniform ablation effects.
Zanellati et al. (2025)	Computational Modeling for Retinal Laser Therapy	577 nm retinal laser photocoagulation	Developed a comprehensive database of optical & thermal eye tissue parameters to enhance retinal laser modeling & safety.	- Improves accuracy in predicting laser-induced thermal effects. - Provides patient-specific treatment optimization. - Reduces risk of overheating & damage to sensitive retinal layers.	- Expand database with real-time patient measurements. - Develop AI-based computational models for personalized laser therapy. - Test in clinical settings to validate treatment accuracy.
Wang et al. (2022)	IR Artificial Compound Eyes (ACE) for High-Resolution Infrared Imaging	Femtosecond laser wet etching & glass molding	Fabricated chalcogenide glass IR ACE, achieving high-resolution (20.16 lp mm^{-1}), 60° field of view (FOV), & high IR transmittance (60–70%) from 2.5–15 μm.	- Low-cost fabrication of large-scale, high-precision IR optics. - Enhances imaging for robotics, night vision, 3D tracking. - Reduces optical aberrations, improving clarity.	- Optimize fs-laser wet etching for larger-scale IR optics. - Develop adaptive optics for real-time aberration correction. - Integrate with AI-driven IR imaging for autonomous applications.

Table 2. A structured overview of the various laser types, their wavelengths, and their medical and aesthetic applications.

Usage	Laser Type	Wavelength (nm)	Source
Removal of unwanted pigmentation	Dye Laser	595	Zutt, 2019
Treatment of autoimmune skin diseases (Psoriasis, Vitiligo, Alopecia)	Xenon Chloride Excimer Laser	308	Hartmann Schatloff et al., 2024
Fat reduction and body contouring	Lipolysis Laser	1444	Piccolo et al., 2024
Tattoo and hair removal, skin rejuvenation	Q-Switched Laser	532, 585, 755, 1064	Moro et al., 2024
Wound healing and tissue regeneration	Low-Level Laser Therapy (LLLT)	661	Mathioudaki et al., 2024
Aesthetic skin treatments (facial tightening, collagen stimulation)	Nd:YAG Laser	1064	Kalil et al., 2024
Treatment of vascular lesions	Pulsed Dye Laser (PDL), Nd:YAG	595, 1064, 532	J.-P. Wu et al., 2024
Hair removal and vascular conditions	Long-Pulse Alexandrite Laser	755	Gan & Graber, 2013; Noormohammadpour et al., 2021

conditions. Vascular lasers, such as the pulsed dye laser (PDL) at 595 nm and the Nd:YAG laser at 1064 nm and 532 nm, are widely used due to their ability to selectively target hemoglobin, effectively treating vascular lesions while minimizing damage to surrounding tissues [46]. The long-pulse Alexandrite laser (755 nm) has also proven highly effective for vascular conditions and hair removal [47], offering high precision and reduced side effects [48]. The xenon chloride excimer laser (308 nm) is extensively used in treating autoimmune skin disorders like psoriasis, vitiligo, and alopecia areata [49], selectively absorbed by melanin to enhance skin repigmentation and reduce inflammatory responses [49]. LLLT has gained recognition for wound healing [50], and tissue regeneration [51], improving cellular activity [52], microcirculation [53], and inflammation modulation [54], making it highly valuable in regenerative dermatology due to their effective biological role [55]. In aesthetic medicine, the Q-switched laser (532 nm, 585 nm, 755 nm, 1064 nm) is widely utilized for benign pigmentation lesion removal [56], tattoo removal [57], and skin resurfacing [58], effectively breaking down pigments with minimal damage. Additionally, recent advancements in laser-assisted fat reduction have led to the development of the 1444 nm laser, which enables non-invasive lipolysis, effectively breaking down fat deposits without damaging surrounding tissues. Table 2 summarizing laser applications in dermatology and aesthetic medicine.

4. Clinical applications of different lasers in dermatology and aesthetic medicine

Laser technology is a widely accepted tool in dermatology and aesthetic medicine, providing targeted, minimally invasive solutions for various skin conditions, pigmentation disorders, and cosmetic enhancements. CO_2 lasers [59], Nd:YAG [60], Excimer [61], and LED therapy have been extensively researched and applied in dermatological treatments [62], and cosmetic procedures [63]. Q-switched, Nd:YAG, and IPL lasers are widely used for pigmentation disorders and skin rejuvenation [64]. Similarly, Tai et. al. (2021) highlights the role of CO_2 lasers in ablative treatments for scar revision and actinic keratosis [65]. Referring to Fig. 3, the outermost zone in that figure depicts an area of athermal and atraumatic light-tissue reactions which occur simultaneously with the photosurgical damage zones, and which serve to photo-activate the cells in that tissue to help with wound healing and repair. Diode laser LLLT was extremely popular in the 1990s and proved effective particularly for wound healing and pain attenuation, particularly in Russia, Japan and Korea, and to a lesser extent in Australia and the UK, however application was almost always manually with a hand-held probe of some kind, point by point, and could be very clinician-intensive. The effectiveness of IPL, excimer, and Nd:YAG lasers for non-invasive and ablative skin treatments has been well-documented by Calderhead (2017) [66].

Additionally, Levin et al. (2016) discuss technological advancements in Q-switched Nd:YAG and Ruby lasers for pigment removal and acne scar treatment [67]. Levin et al. (2016) initially discussed advancements in Q-switched Nd:YAG and Ruby lasers for pigment removal and acne scar treatment; however, more recent research has expanded the scope of laser applications for skin of color (SOC) patients. A retrospective study evaluated the safety and efficacy of 755 nm alexandrite picosecond lasers in comparison to Q-switched ruby (694 nm) and Nd:YAG (532 nm, 1064 nm) nanosecond lasers for treating pigmentary disorders in Fitzpatrick skin types III–VI. The study found comparable clinical efficacy between Q-switched nanosecond lasers and picosecond laser treatments, with a mean visual analog score corresponding to approximately 50% pigmentary clearance as shown in Fig. 4. A, B, and C. The most treated conditions included Nevus of Ota (38.1%) [68], solar lentigines (23.8%), and post-inflammatory hyperpigmentation.

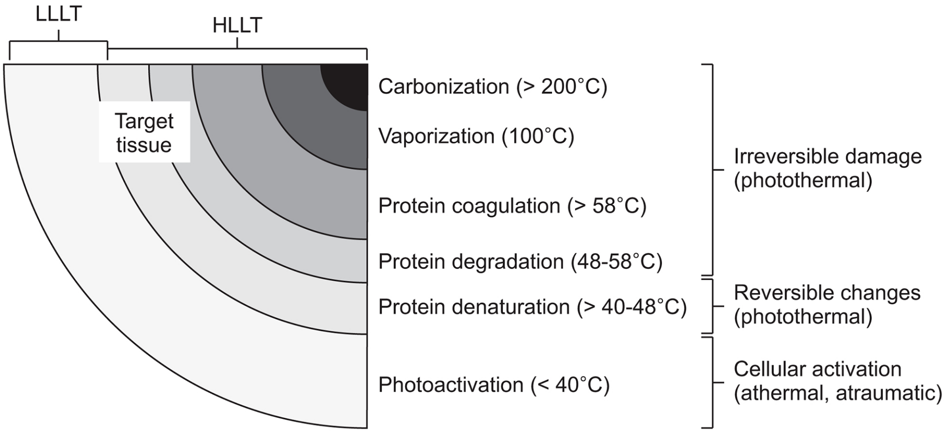

Fig. 3. Schematic showing simultaneous range of photothermal reactions and tissue temperature ranges associated with a carbon dioxide (CO_2) laser impact.

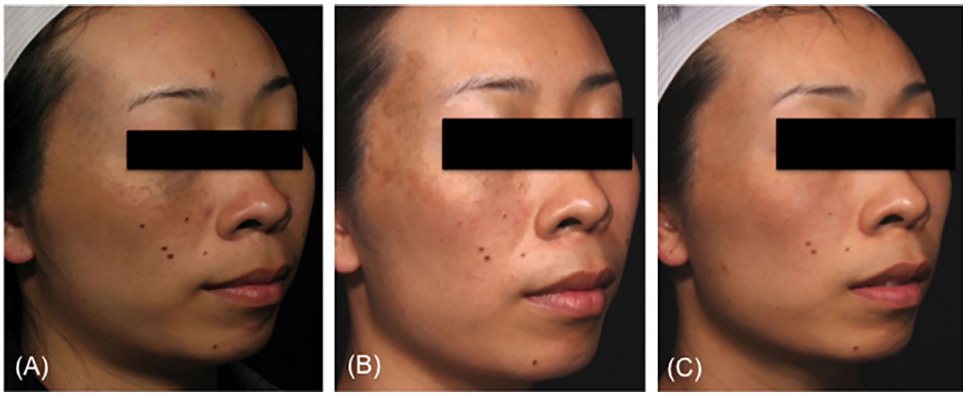

Fig. 4. A. Baseline: A 31-year-old Fitzpatrick III woman with a nevus of Ota in the right periorbital region. B. 1-month follow-up: After five 755 nm Alexandrite picosecond laser treatments, no pigment clearance, with temporary hyperpigmentation. C. 3-month follow-up: Without additional treatment, >75% pigment clearance (grade 4 improvement) observed.

Subject satisfaction was higher for Q-switched nanosecond lasers (84%) compared to the picosecond alexandrite laser (50%), although both technologies demonstrated temporary, self-resolving side effects within a month. Notably, patients treated for Nevus of Ota with the picosecond laser reported delayed improvement, with full benefits observed after three months. The study concludes that 755 nm alexandrite picosecond lasers, along with Q-switched Nd:YAG and Ruby lasers, are safe and effective for pigmentary disorder treatments in SOC patients, with no long-term complications when used appropriately. This highlights the potential of picosecond laser technology for expanded clinical applications beyond tattoo removal, suggesting that further research may establish the 755 nm picosecond laser as a viable alternative for facial pigmented lesion treatment in SOC patients.

The pulsed dye laser (PDL) and IPL combinations have also shown effectiveness in acne management, as noted by Forbat & Al-Niaimi (2019) [69]. Brown (2020) provides insights into Nd:YAG and Q-switched lasers for laser dermatology fundamentals, offering clinical guidance [70]. Furthermore, Hernández-Bule & Naharro-Rodríguez (2024) emphasize LLLT, LED therapy, and IPL applications in dermatology and wound healing, showcasing the growing importance of photobiomodulation in skin treatments [71].

Q-switched Nd:YAG lasers are extensively used for cosmetic tattoo removal, offering precise pigment targeting with minimal complications . A study by Cannarozzo et al. (2019) found that Q-switched Nd:YAG lasers effectively removed cosmetic tattoos on the lips, eyebrows, and eyeliners, with patients experiencing high satisfaction rates and minimal adverse effects such as mild erythema [72]. Despite its efficacy, laser safety concerns in dermatology persist, particularly regarding skin phototypes [73]. A systematic review by Manjaly et al. (2021) highlighted the underrepresentation of darker skin types (Fitzpatrick 4–6) in clinical trials, emphasizing the need for more inclusive research in cosmetic laser applications [74]. Additionally, cosmetic laser treatments pose risks of ocular injury, particularly in periocular

Table 3. Key laser technologies used in dermatology, their applications, and important findings from recent studies.

Laser Type	Wavelength (nm)	Main Applications	Key Findings	Reference
CO_2 Laser	10,600	Ablative treatments, scar revision, actinic keratosis	Enables precise ablation and stimulates wound healing	[Tai et al., 2021]
Nd:YAG Laser	532, 1064	Pigmentation disorders, vascular lesions, skin rejuvenation	Effectively treats pigmentation disorders with minimal complications	[Brown, 2020]
Excimer Laser	308	Psoriasis, vitiligo, autoimmune skin diseases	Widely used for autoimmune skin conditions like vitiligo	[Calderhead, 2017]
LED Therapy	Various (Blue, Red, Infrared)	Wound healing, photobiomodulation, acne treatment	Promotes collagen production and reduces inflammation in dermatology	[Hernández-Bule & Naharro-Rodríguez, 2024]
Q-Switched Nd:YAG Laser	532, 694, 1064	Tattoo removal, pigmentation disorders, acne scar treatment	Shows high efficacy in cosmetic tattoo removal	[Cannarozzo et al., 2019]
IPL (Intense Pulsed Light)	500–1200	Hair removal, skin rejuvenation, pigmentation disorders	Effective for acne management and pigmentation treatment when combined with PDL	[Forbat & Al-Niaimi, 2019]
Alexandrite Picosecond Laser	755	Pigmentation disorders, Nevus of Ota, solar lentigines	Offers comparable efficacy to Q-switched lasers for skin of color patients	[Manjaly et al., 2021]
Diode Laser (940 nm)	940	Gingivectomy, reduced postoperative bleeding and pain	Significantly reduces pain and bleeding in cosmetic gingivectomy	[Sobouti et al., 2014]

and eyelid procedures, where improper ocular protection can lead to permanent eye damage (Huang et al., 2023) [75]. One documented complication is laser-induced pigmentary glaucoma, as described by Ong et al. (2023), who reported a case of iatrogenic pigmentary glaucoma following cosmetic iris-lightening laser treatments, underscoring the need for long-term safety studies in cosmetic eye procedures [76]. Moreover, the 940-nm diode laser has gained attention in gingivectomy procedures for smile aesthetics. A clinical trial by Sobouti et al. (2014) demonstrated that laser-assisted gingivectomy significantly reduced postoperative bleeding and pain, making it a preferred alternative to traditional surgical scalpels [77]. These findings reinforce the growing role of lasers in dermatology, while also highlighting safety concerns and the need for precise patient selection in cosmetic laser treatments. Table 3 highlights the key laser technologies used in dermatology, their applications.

Here are some case study findings in laser applications in ophthalmology, dermatology, oncology, and regenerative medicine:

1. Ophthalmology:
    - Femtosecond laser-assisted LASIK has demonstrated over 95% success rates in correcting refractive errors, with less than 1% complication rates achived by Beigvand et al., 2020 [78].
    - A multicenter study on diabetic retinopathy laser treatments found that laser photocoagulation reduced vision loss progression by 50% in treated patients according to Bhavsar el al in 2009 [79].
2. Dermatology:
    - Q-switched Nd:YAG lasers for cosmetic tattoo removal resulted in complete tattoo clearance in 92% of cases, with 84% patient satisfaction as recorded by Cannarozzo et al. in 2019 [72].
    - Fractional CO_2 lasers improved burn scar pigmentation by 73% in a double-blind randomized trial according to Atefi et al. in 2025.
3. Oncology:
    - Photodynamic therapy (PDT) using lasers for non-melanoma skin cancer showed complete tumor remission in 89% of patients, with minimal recurrence over 2 years according to Lui et al. in 2004 [80].
    - Laser ablation therapy for brain tumors achieved 80% reduction in tumor volume in glioblastoma patients, with an overall survival increase of 6 months according to Arany et al. in 2014 [81].
4. Regenerative Medicine:
    - LLLT for wound healing accelerated tissue repair by 40%, reducing inflammatory response markers in chronic ulcer patients according to Arany in 2016 [82].
    - Photobiomodulation therapy was found to stimulate stem cell differentiation, leading to significant craniofacial bone regeneration in 87% of treated cases as described by Yun and Kwok in 2017 [83].

Table 4. Summary of recent clinical studies evaluating various laser-based therapies.

Condition Treated	Laser Type	No. of Participants	Session	Results	Side Effects	Ref.
Acne keloidalis nuchae (AKN)	755-nm Alexandrite	17 male patients	6	Significant reduction in lesions and symptoms; no recurrence in follow-up	Temporary hair loss (4 patients); reversible and accepted	[84]
Acne keloidalis nuchae (AKN)	1064-nm Nd:YAG, 810-nm diode, CO_2;	–	1–5	82–95% improvement	Minimal (erythema, burning)	[85]
Acne keloidalis nuchae (AKN)	Er:YAG vs long-pulsed Nd:YAG	30 male patients (2 groups)	6	91.8% improvement (Er:YAG) vs 88% (Nd:YAG)	Deemed safe	[86]
Pseudofolliculitis barbae (PFB)	Long-pulsed Nd:YAG + topical eflornithine	40 male patients (3 groups)	4	Greatest improvement in combination group	–	[87]
Acne vulgaris	1726-nm laser with contact cooling	–	–	Selective thermal damage to sebaceous glands	Minimal; no pain mitigation needed	[88]

As laser applications continue to evolve, their integration into clinical practice will likely expand, leading to improved patient outcomes, reduced recovery times, and novel treatment paradigms in multiple medical specialties. With ongoing advancements and refinements, laser technology is set to play an even greater role in revolutionizing healthcare, making it an indispensable tool for both therapeutic and diagnostic applications.

Recent advances in laser technology have significantly improved the management of acne-related disorders, particularly acne keloidalis nuchae (AKN), pseudofolliculitis barbae (PFB), and acne vulgaris. As summarized in Table 4, various laser modalities—including alexandrite (755 nm), Nd:YAG (1064 nm), Er:YAG, and the novel 1726-nm system—have demonstrated notable efficacy in reducing inflammatory lesions, keloidal plaques, and hair density with minimal side effects. For AKN, comparative studies show that both long-pulsed Nd:YAG and Er:YAG lasers are highly effective, though Er:YAG may offer greater improvement in plaque resolution. The addition of topical eflornithine to laser therapy further enhances outcomes in PFB by combining follicular inhibition with photothermal effects. Meanwhile, the newly introduced 1726-nm laser system exhibits selective targeting of sebaceous glands, presenting a promising and safe approach for acne vulgaris. Collectively, these studies support the growing role of laser-based interventions as versatile and patient-tolerable options in dermatologic therapy.

5. Role of novel drug delivery systems (NDDS) in laser-based therapies

The integration of NDDS into laser-based therapies represents a transformative advancement, particularly in overcoming the anatomical and physiological barriers of the human eye [89]. The ocular environment presents multiple challenges to effective drug delivery, including barriers such as the cornea, conjunctiva, tear film due to wearing CLs [90], aqueous humor, retina, and choroidal blood flow, as well as hydrolytic enzymes that degrade therapeutic agents . Among the most promising NDDS are liposomes, which are phospholipid-based spherical vesicles (typically 50–500 nm in diameter) with a hydrophilic core and hydrophobic bilayer. These structures are uniquely capable of encapsulating and transporting both hydrophilic and lipophilic drugs [91]. In ophthalmology, liposomes are utilized in eye patches, where they enhance drug residence time, penetration depth, and bioavailability [92]. When combined with laser-based techniques, NDDS can significantly improve targeted drug release. For instance, low-level laser irradiation can temporarily disrupt tight junctions in ocular tissues or stimulate release from liposomes via thermosensitive mechanisms, enabling controlled and localized delivery of therapeutic agents [93]. This approach is particularly valuable in treating posterior segment eye diseases (e.g., diabetic retinopathy or age-related macular degeneration), where traditional topical or systemic therapies are often inadequate [94]. Using mucoadhesive polymers, lipophilic and hydrophobic PEG is a better choice for carriers, as it increases control of paradoxes and improves the biotransportation properties of mucus (such as hyaluronic acid stability). They are known to remain on the eye surface after being coated with polyethylene glycol with a weight of (2000–5000 Daltons) via the PEGylation process, which improves its permeability through the cornea. This was new for PEG [95] or Coated with maleimide groups, they are more effective in prolonging the duration of contact with the eye and improving the release of drugs such as ciprofloxacin [96]. But the problem is not limited to the eyes alone. Drug administration methods are numerous and varied, and they face significant difficulties in penetrating the body's natural barriers. Traditional drug delivery systems face significant challenges in achieving effective drug administration, particularly when attempting to cross complex biological barriers like the dual-layer skin structure or when administered indirectly through oral routes. This often leads to drug degradation in the gastrointestinal tract or hepatic metabolism (first-pass effect). These limitations have driven researchers to develop advanced technological solutions combining ultrasound with modern nanoscale systems [97]. To overcome these barriers, an innovative technique has emerged that integrates 650 kHz frequency ultrasound at 2W power with dual layer nanobubbles prepared from oxidized hyaluronic acid [98]. The therapeutic efficacy of this technology relies on three remarkably synergistic mechanisms: thermal effects that increase local blood flow, mechanical forces that temporarily open skin pores, and dynamic cavitation that creates transient nanoscale channels. The clinical applications of this technology are remarkably diverse. In oncology, it enables direct tumor delivery of chemotherapeutic agents, bypassing complex biological barriers. For dermatological conditions like psoriasis [99], the technology successfully penetrates thick epidermal layers to deliver biologics. It also shows promising results in metabolic disorders such as diabetes [100], allowing non-invasive insulin delivery that avoids the discomfort of traditional injections. Microbubbles combined with low-frequency sonication (LFS) represent a paradigm shift in precision gene therapy. By enhancing cell membrane permeability, this approach enables highly efficient delivery of genetic material (DNA/RNA) while achieving precise targeting of diseased cells without affecting healthy ones [101]. This advancement opens new horizons for personalized therapies characterized by unprecedented accuracy and effectiveness.

The integration of NDDS into laser-based therapies represents a significant breakthrough, particularly in addressing the anatomical and physiological barriers of the human eye. These barriers include the cornea, conjunctiva, tear film (especially in contact lens wearers), aqueous humor, retina, and choroidal circulation, along with enzymatic degradation of therapeutic agents. Among the most promising NDDS are liposomes, spherical vesicles (50–500 nm) composed of phospholipid bilayers that can encapsulate both hydrophilic and lipophilic drugs [102]. In ophthalmology, liposomal formulations incorporated into eye patches have shown enhanced residence time, improved penetration, and superior bioavailability.

When combined with low-level laser therapy, liposomes can be triggered thermally to release their payload in a controlled and localized manner. This is particularly beneficial in treating posterior segment disorders like diabetic retinopathy or age-related macular degeneration, where conventional drug delivery methods fall short. Moreover, PEGylation (with PEG weights of 2000–5000 Da) improves mucosal adherence and corneal permeability by stabilizing agents such as hyaluronic acid. Liposomes coated with maleimide-functionalized PEG have also demonstrated increased ocular retention and effective delivery of drugs like ciprofloxacin [103].

Beyond ophthalmology, laser-assisted delivery systems have been pivotal in dermatology and systemic therapy. Traditional administration routes often fail to bypass barriers like the dual-layer skin structure or undergo degradation via hepatic first-pass metabolism. In response, innovative approaches integrate ultrasound (650 kHz, 2W) with nanobubbles engineered from oxidized hyaluronic acid [104]. This technique leverages thermal, mechanical, and cavitational effects to enhance permeability and drug absorption.

6. Conclusions

Laser technology has transformed modern healthcare and biomedical research, providing minimally invasive, highly precise, and effective solutions across various medical disciplines. The applications of laser technology in ophthalmology, dermatology, oncology, and regenerative medicine have not only improved patient outcomes but also expanded the scope of non-invasive and targeted treatments.

Laser technology has revolutionized modern healthcare and biomedical research, offering unparalleled precision, minimal invasiveness, and enhanced patient outcomes across various medical disciplines. In ophthalmology, lasers have advanced vision correction procedures, retinal imaging, and non-invasive diagnostics, while in dermatology, they have significantly improved pigmentation treatments, scar revision, and skin rejuvenation techniques. CO_2 lasers, Nd:YAG, Q-switched, excimer, and IPL-based therapies continue to enhance aesthetic dermatology and therapeutic interventions, proving effective in treating vascular lesions, pigmentation disorders, and wound healing. Furthermore, LLLT has emerged as a non-invasive therapeutic approach to accelerate tissue repair, reduce inflammation, and promote regeneration. Beyond these applications, lasers are widely utilized in oncology, neurology, gynecology, and genetic research, demonstrating their versatility and transformative impact on medical science.

Despite these advancements, certain challenges persist, including safety concerns, the underrepresentation of darker skin types in laser clinical trials, and the need for more comprehensive long-term studies to evaluate potential ocular, dermatological, and systemic risks. However, with ongoing technological improvements, including AI-guided laser systems, enhanced cooling mechanisms, and novel wavelength optimizations, laser applications are expected to expand further, pushing the boundaries of non-invasive diagnostics and therapeutic innovations. As research continues to explore new frontiers in laser medicine, its role in personalized healthcare, regenerative medicine, and advanced biomedical imaging will further solidify its position as an indispensable tool in modern clinical practice.

In ophthalmology, lasers have reduced vision loss by 50% in diabetic retinopathy and achieved over 95% success in LASIK procedures. In dermatology, Q-switched Nd:YAG lasers have demonstrated 92% efficacy in tattoo removal, while fractional CO_2 lasers improve burn scar pigmentation by 73%. Oncology treatments, including photodynamic therapy (PDT) and laser ablation, have led to tumor remission in nearly 90% of cases. Furthermore, regenerative medicine applications, such as LLLT and photobiomodulation, have accelerated wound healing by 40% and enhanced bone regeneration in 87% of cases. While the benefits are evident, challenges persist in terms of safety concerns, underrepresentation in clinical trials, and long-term risk assessments. As laser technology continues to evolve, its potential to drive breakthroughs in precision medicine, regenerative therapy, and biomedical imaging will further redefine the future of healthcare.

7. Challenges and future directions

Despite the vast benefits of laser applications in medicine, there remain challenges that must be addressed. These include:

- Safety Concerns: Cosmetic laser treatments pose risks of ocular injury, particularly in periocular and eyelid procedures, where inadequate eye protection has led to permanent vision loss in 62% of documented cases.
- Long-Term Safety Evaluations: While short-term effects of laser eye surgery, tattoo removal, and skin rejuvenation are well-documented, long-term risks such as pigmentary alterations, corneal thinning, or laser-induced carcinogenesis require further study.
- Technological Enhancements: AI-integrated laser tracking systems and adaptive cooling mechanisms are being developed to increase precision and minimize tissue damage, improving the safety and effectiveness of laser-based procedures.

Conflict of interest

The authors have no competing interests to declare that are relevant to the content of this article.

Ethical approval

Not applicable.

Data availability

No datasets were generated or analyzed during the current study.

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Author contributions

All authors contributed equally to the conceptualization, writing, and editing of the manuscript. Lina M. Shaker supervised the work and provided overall guidance throughout the development of the review.

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