Journal of Clinical and Nursing Research, 2026, Volume 10, Issue 3
http://ojs.bbwpublisher.com/index.php/JCNR
Online ISSN: 2208-3693
Print ISSN: 2208-3685

Advances in Mechanisms and Clinical Applications of Lasers with Different Wavelengths in Medicine

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Abstract: Since its inception, laser technology has undergone a leapfrog development from fundamental exploration to extensive clinical applications. In its early stages, lasers were mainly used for simple tissue cutting. With continuous technological innovation, their clinical value in precision therapy and minimally invasive intervention has become increasingly prominent. Lasers have evolved into an indispensable tool for the treatment of numerous diseases, driving a paradigm shift in diagnosis and treatment within the medical field. Lasers of different wavelengths exhibit significant differences in penetration depth and absorption characteristics within biological tissues. This wavelength selectivity enables lasers to act precisely on target tissues while minimizing damage to surrounding normal tissues. For instance, specific wavelengths can be selectively absorbed by chromophores such as melanin and hemoglobin, thereby achieving precise treatment of related diseases. This constitutes the fundamental mechanism underlying the precision of medical lasers. This review aims to systematically summarize recent advances in the working principles, expanded clinical applications, and cutting-edge research trends of various wavelengths of lasers in medicine. It is intended to provide comprehensive and up-to-date references for researchers and clinicians in related fields, and to promote the further development and application of medical laser technology.

Keywords: Photothermal effect; Tissue optics; Absorption coefficient

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1. Introduction

Lasers with different wavelengths exhibit diverse mechanisms of action and clinical application potentials, due to their differences in tissue penetration depth, absorption properties, and photothermal, photochemical, or photomechanical effects. Low-intensity lasers in the visible to near-infrared range can regulate cellular redox status, activate signaling pathways, and promote tissue repair and anti-inflammatory responses. In contrast, high-energy mid- and far-infrared lasers mainly rely on thermal effects to achieve tissue ablation, coagulation, or remodeling, and are widely used in surgery, skin scar treatment, and urinary calculus management. With the development of precision medicine, the integration of intelligent optical systems and novel laser sources (such as ultrashort-pulse lasers and quantum cascade lasers) has further improved the targeting and safety of treatments. In recent years, the emergence of advanced technologies, including fractional lasers, transcranial photobiomodulation, and additive manufacturing combined with laser navigation, has promoted the in-depth exploration of lasers in neurological rehabilitation, tissue repair, and minimally invasive interventions. Therefore, systematically clarifying the mechanisms underlying the relationship between laser wavelength and biological effects, and summarizing the translational progress in multidisciplinary clinical practice, is of great significance for optimizing treatment strategies and expanding application boundaries.

2. Classification and basic mechanisms of lasers

2.1. Selective photothermolysis

Lasers of specific wavelengths can be selectively absorbed by chromophores in target tissues, such as melanin and hemoglobin [1]. The absorbed energy is converted into heat, which causes coagulation, vaporization, or necrosis of target tissues. Since surrounding normal tissues absorb little laser energy, they are minimally damaged.

2.2. Photomechanical/photoacoustic effects (targeted photolysis mechanism of picosecond lasers)

Picosecond lasers have an extremely short pulse duration and can release high energy in a very short time, generating strong photomechanical shock waves [2]. Such shock waves mechanically fragment target substances such as pigment particles. The fragmented particles are then phagocytosed and cleared by phagocytes in the body to achieve therapeutic effects. Meanwhile, laser energy also induces photoacoustic effects and generates ultrasonic waves, which can be used for tissue imaging and disease diagnosis [3].

2.3. Thermal coagulation and vaporization effect

Mid-infrared lasers have relatively long wavelengths and shallow penetration depth in tissues, but exhibit strong thermal effects. When laser energy is applied to tissues, the tissue temperature rises rapidly, leading to thermal coagulation and subsequent scar tissue formation, which achieves tissue repair and remodeling [4].

2.4. Photobiomodulation effect

Low-power lasers have low energy and do not cause obvious thermal damage to tissues. However, they can affect cell metabolism, proliferation, and differentiation through photobiomodulation [5]. They can activate multiple intracellular enzyme systems, promote the release of cytokines, regulate inflammatory responses, and accelerate tissue repair and regeneration. They show important application value in the treatment of inflammatory diseases and the repair of tissue injuries.

3. Working principles and clinical applications of lasers at various wavelength bands

Ultraviolet lasers (100–400 nm) have high photon energy and can break molecular bonds in tissue cells, leading to photochemical ablation [6]. They are clinically used in corneal refractive surgery (PRK, LASIK assistance) and pretreatment for epidermal grafting in vitiligo. In corneal refractive surgery, photorefractive keratectomy (PRK) uses ultraviolet lasers to directly ablate the corneal anterior limiting lamina and superficial stroma, thereby changing corneal curvature to correct myopia, hyperopia, and astigmatism [7]. Recent studies have explored the mechanism of skin in-situ regeneration and repair mediated by ultraviolet lasers. It has been found that ultraviolet lasers can activate skin stem cells, promote their proliferation and differentiation, and regulate cytokine secretion to accelerate skin tissue regeneration and repair [8]. This discovery provides a new theoretical basis for the application of ultraviolet lasers in skin injury repair and is expected to support the development of more effective treatments.

Visible-wavelength lasers (400–760 nm) exhibit strong absorption by chromophores such as hemoglobin and melanin. When laser energy is applied to tissue, hemoglobin and superficial melanin selectively absorb laser energy and convert it into heat. As a result, the diseased tissue is damaged, while the surrounding normal tissue is minimally injured [9]. Visible-wavelength lasers include argon lasers, copper vapor lasers, ruby lasers, and others. Argon laser energy is selectively absorbed by hemoglobin in capillaries, leading to capillary coagulation and occlusion. It can also act on blood vessels and inflamed tissue at the lesion site to reduce inflammation, and is used in the treatment of telangiectasia and rosacea [10]. Copper vapor lasers can activate photosensitizers to generate cytotoxic reactive oxygen species, which destroy vascular endothelial cells in the lesion, thus achieving a therapeutic effect on port-wine stains [11]. The heat generated by ruby lasers breaks down pigment granules in the epidermis, which are then removed by phagocytes. This laser is used to treat epidermal pigmentary diseases such as freckles and café-au-lait spots. Meanwhile, the laser energy can also target melanin in hair follicles and destroy follicular tissue to achieve permanent hair removal.

Near-infrared lasers (760–2500 nm) have relatively long wavelengths and deeper penetration depth in tissues, allowing them to reach deep dermal and even subcutaneous tissues [12]. They can also induce photoacoustic effects, which help clinicians evaluate the status of diseased tissues; the mechanical force generated by photoacoustic effects can also disrupt abnormal tissues to a certain extent, achieving synergistic therapeutic outcomes with the photothermal effects of lasers. Common near-infrared lasers include alexandrite lasers, Nd:YAG lasers, and picosecond lasers [13]. Alexandrite lasers can penetrate into the dermis and be selectively absorbed by melanin, and are mainly used for the treatment of nevus of Ota and dark tattoo removal [14]. Nd:YAG lasers target deep vascular and pigmented tissues; after the energy is absorbed by hemoglobin in blood vessels, thermal energy is produced to coagulate and occlude vessels, so Nd:YAG lasers are applied in the treatment of hemangiomas and can also improve pigmented lesions. Picosecond lasers have an extremely short pulse width and release high energy in a short time, generating strong photomechanical shock waves that effectively break down pigment particles, leading to significant efficacy in the treatment of freckles and melasma; picosecond lasers can also stimulate the regeneration and rearrangement of collagen, and are used for scar repair and facial rejuvenation [15,16].

Mid-infrared lasers (2500 nm–1 mm) have long wavelengths and strong water absorption. When laser energy is applied to tissue, water molecules in the tissue absorb a large amount of laser energy, which is rapidly converted into heat, leading to an increase in tissue temperature [17]. Such thermal energy can induce tissue thermal coagulation, vaporization, or thermal remodeling. Clinical applications mainly include erbium lasers and carbon dioxide lasers. The 2940 nm erbium laser exhibits extremely strong water absorption and can vaporize water molecules in the superficial tissue within a very short time, allowing precise skin resurfacing and improving skin roughness, wrinkles, or skin scars [18]. The 10600 nm carbon dioxide laser causes tissue coagulation and vaporization through thermal effects, and simultaneously stimulates the regeneration and rearrangement of dermal collagen, achieving tissue repair and remodeling. It is used for the excision of benign neoplasms and the treatment of skin ulcers.

Other special-wavelength lasers include 980 nm diode lasers and 830 nm low-power lasers. The 980 nm diode laser shows good tissue penetration and selective absorption by hemoglobin. In the treatment of vascular proliferative diseases such as strawberry hemangioma and port-wine stain, the 980 nm diode laser causes coagulation and occlusion of pathological blood vessels through thermal coagulation, thus inhibiting vascular proliferation and achieving therapeutic effects. The 830 nm low-power laser can inhibit the release of inflammatory factors such as tumor necrosis factor-α and interleukin-6, and reduce inflammatory responses. It also activates the endogenous analgesic system and promotes the release of analgesic substances such as opioid peptides to relieve pain, so it is used for the treatment of postherpetic neuralgia.

4. Latest advances in lasers across disciplines

4.1. Photodynamic and low-level photobiomodulation therapy

In recent years, based on the penetration characteristics of lasers with different wavelengths in biological tissues and their interaction mechanisms with cellular photoreceptors, low-level photobiomodulation therapy (PBM) has gradually become a promising non-invasive treatment in the medical field. PBM involves the absorption of specific red and near-infrared light by mitochondrial cytochrome c oxidase, triggering a cascade of biological effects, regulating reactive oxygen species levels, ATP synthesis, and signal transduction pathways, and ultimately affecting cell proliferation, anti-inflammation, and tissue repair processes [19]. Dompe et al. described the molecular mechanisms of PBM and confirmed that the activation of redox-sensitive pathways is crucial for tissue repair. Near-infrared low-level lasers can significantly promote cell proliferation by regulating redox-sensitive signaling pathways, providing theoretical support for wound healing and regenerative medicine. Although the pro-repair effects of PBM have been verified, inappropriate parameter settings may cause thermal damage or ineffective intervention. Dosage and wavelength must be strictly controlled in clinical applications. The efficacy of PBM is not universal, and precise regulation is required according to individual differences. PBM is applied in neurocognition and pain management. PBM may alleviate neurodegenerative diseases by enhancing mitochondrial function in the brain. PBM has significant analgesic effects, and its mechanisms involve the inhibition of inflammatory factor release and the regulation of neuronal excitability.

4.2. Applications of lasers in skin and scar treatment

With the rapid development of optoelectronic technology, lasers with different wavelengths have become an important research direction in medical aesthetics and wound repair for skin tissue regeneration and scar treatment. Various lasers achieve precise intervention in collagen remodeling, microcirculation reconstruction, and inflammation regulation in scar tissue through selective photothermolysis, photomechanical effects, and photobiomodulation [20]. From non-ablative fractional lasers to high-energy carbon dioxide lasers, the optimized combination of wavelength, pulse width, and energy density has significantly improved the safety and efficacy of treatment. Numerous studies have shown that lasers with different wavelengths can effectively regulate key pathological processes in scar tissue, including collagen remodeling, angiogenesis, and inflammatory responses, via selective photothermolysis or photomechanical effects. Especially in the treatment of hypertrophic scars and contracture scars, fractional carbon dioxide lasers exhibit prominent clinical advantages by promoting epidermal regeneration and stimulating orderly dermal repair due to their micro-ablative properties [21]. The mechanism of laser therapy for scars not only relies on the wound healing cascade induced by thermal injury but also involves the molecular regulation of signaling pathways such as TGF-β/Smad and the phenotypic transformation of fibroblasts [22].

4.3. Laser technologies in ophthalmology and minimally invasive interventions

From photocoagulation for retinal diseases to endovascular plaque ablation, lasers have improved the accuracy and safety of surgery and promoted the development of intelligent optical assistance systems [23]. The selection of laser wavelengths directly affects the interaction mechanism between lasers and biological tissues as well as the clinical efficacy. Micropulse lasers are widely used in the treatment of chronic retinal diseases such as diabetic macular edema and central serous chorioretinopathy due to their controllable thermal effects and selective action on the retinal pigment epithelium, avoiding photocoagulation scars and visual field defects caused by traditional continuous-wave lasers [24,25]. Micropulse lasers achieve subthreshold photodamage through intermittent energy delivery, activate retinal repair mechanisms while preserving the function of photoreceptors, and significantly expand the therapeutic safety window [25]. In minimally invasive interventional therapy, laser technology has been gradually integrated with intelligent optical imaging, navigation and feedback systems, improving ablation accuracy and intraoperative evaluation capability. Laser ablation systems based on specific wavelengths (such as 1470 nm or 1940 nm) combined with fiber-optic sensing and artificial intelligence algorithms allow precise control of thermal damage in endovascular or solid tumor interventions, reducing collateral damage to surrounding healthy tissues.

4.4. Applications of lasers in urology, surgical operations and other medical fields

In the field of urology, lasers have become one of the core methods for stone treatment due to precise energy delivery and controllable thermal effects. Liang et al. reported that holmium laser under ureteroscopy can effectively fragment stones, but the risk of local tissue damage caused by heat accumulation should be noted [26]. Taratkin et al. further compared the stone fragmentation mechanisms of Ho:YAG and thulium fiber lasers in different medium environments, and pointed out that wavelength and pulse characteristics significantly affect ablation efficiency and thermal diffusion range. Pulsed dye lasers and copper vapor lasers achieve selective photothermal destruction of lesions by matching hemoglobin with their specific absorption spectra, while protecting surrounding tissues to the maximum extent. Overall, lasers with different wavelengths exhibit highly specialized clinical efficacy in urological lithotripsy, precision surgery, wound repair, vascular therapy and other aspects due to their different interaction mechanisms with biological tissues.

4.5. Advances in the integration of emerging optical technologies and multimodal diagnosis and treatment

From the visible and near-infrared to mid-infrared and even terahertz bands, the penetration depth, selective absorption, and photochemical effects of lasers have been systematically applied in many clinical fields, including tumor ablation, skin repair, neural regulation, and chronic disease management. With the development of intelligent imaging guidance, combined photodynamic and photothermal therapy, and multifunctional nanoprobes, optical diagnosis and treatment are evolving toward real-time feedback, personalized intervention, and minimally invasive high efficiency. This process has promoted the technological upgrading of traditional laser devices and provided new theoretical foundations and practical approaches for integrated medical solutions across scales and with multiple parameters. Intelligent precision optical diagnosis and treatment technologies, by integrating wavelength-tunable lasers, real-time imaging, and feedback systems, have significantly improved the targeting and safety of treatment. In photodynamic therapy, the combination of new photosensitizers and specific-wavelength lasers has enhanced the selective killing efficiency of tumor cells and extended its applications in anti-infection and immunoregulation. Meanwhile, short-wave infrared ultrafast fiber laser systems have offered new possibilities for noninvasive intervention in deep tissues due to their large penetration depth and low tissue scattering. In skin aesthetics, the differential effects of lasers with different wavelengths on pigment, blood vessels, and collagen have been widely used, but no unified standards have been established for personalized parameter setting.

5. Conclusion

This review systematically summarizes the research advances in the mechanisms of action and clinical applications of lasers with different wavelengths in the medical field. Lasers of varying wavelengths exhibit distinct interaction modes with biological tissues, which mainly depend on their penetration depth, absorption characteristics, and thermal effect controllability—these differences determine their unique advantages and application scopes in clinical practice. Specifically, short-wavelength lasers are characterized by strong surface absorption, making them suitable for superficial tissue treatment such as skin repair and superficial tumor ablation; mid-wavelength lasers, represented by Ho:YAG lasers, have moderate penetration depth and controllable thermal effects, and are widely used in urological lithotripsy and minimally invasive surgery; long-wavelength lasers, including near-infrared and terahertz lasers, possess deep tissue penetration and low scattering properties, providing new approaches for deep tumor diagnosis and noninvasive intervention.

In clinical applications, lasers with different wavelengths have been maturely applied in multiple disciplines such as urology, dermatology, oncology, and neurosurgery, significantly improving the efficacy of disease treatment, reducing trauma, and promoting patient recovery. With the continuous development of related technologies, the combination of lasers with intelligent imaging guidance, nanomaterials, and synergistic therapy has further optimized their targeting and safety, overcoming the limitations of traditional laser treatment such as tissue damage caused by heat accumulation.

However, there are still some challenges in the clinical application of lasers of different wavelengths: the standardized setting of individual treatment parameters has not been fully established, the long-term safety of some new laser technologies needs to be further verified, and the cost of high-performance laser equipment limits their popularization. In the future, with in-depth research on the interaction mechanisms between lasers and biological tissues, and the continuous innovation of laser equipment and auxiliary technologies, lasers of different wavelengths will show broader application prospects in personalized treatment, precise minimally invasive intervention, and chronic disease management, bringing new breakthroughs to the development of modern medicine.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Kasai K, 2017, Picosecond Laser Treatment for Tattoos and Benign Cutaneous Pigmented Lesions. Laser Therapy, 26(4): 274–281.

[2] Jung D, Seung N, Seo S, et al., 2024, Skin Rejuvenation through Topical Application of Indocyanine Green with Diffractive Optical Element Mode of 785 nm Picosecond Laser in Asian Females. Journal of Cosmetic Dermatology, 23(7): 2411–2419.

[3] Dogra V, Chinni B, Valluru K, et al., 2013, Multispectral Photoacoustic Imaging of Prostate Cancer: Preliminary Ex-vivo Results. Journal of Clinical Imaging Science, 3: 41.

[4] Kuehlmann B, Stern-Buchbinder Z, Wan D, et al., 2019, Beneath the Surface: A Review of Laser Remodeling of Hypertrophic Scars and Burns. Advances in Wound Care, 8(4): 168–176.

[5] Gonçalves A, Monteiro F, Brantuas S, et al., 2025, Clinical and Preclinical Evidence on the Bioeffects and Movement-Related Implications of Photobiomodulation in Orthodontic Tooth Movement: A Systematic Review. Orthodontics and Craniofacial Research, 28(1): 12–53.

[6] Venugopalan V, Nishioka N, Mikić B, 1995, The Thermodynamic Response of Soft Biological Tissues to Pulsed Ultraviolet Laser Irradiation. Biophysical Journal, 69(4): 1259–1271.

[7] Shortt A, Allan B, Evans J, 2013, Laser-Assisted In-Situ Keratomileusis versus Photorefractive Keratectomy for Myopia. Cochrane Database of Systematic Reviews, 2013(1): CD005135.

[8] Wang J, Cheng B, 2010, Effects of Medium-Wave Ultraviolet Radiation on the Expression of Certain Marker Molecules in Cultured Skin Stem Cells In Vitro. Chinese Journal of Dermatology, 43(10): 726–729.

[9] Ash C, Dubec M, Donne K, et al., 2017, Effect of Wavelength and Beam Width on Penetration in Light-Tissue Interaction Using Computational Methods. Lasers in Medical Science, 32(8): 1909–1918.

[10] Boergen K, Birngruber R, Gabel V, et al., 1977, Selective Coagulation of Small Vessels by Means of Argon Laser: Intravital Microscopic Studies. Berichte der Deutschen Ophthalmologischen Gesellschaft, 74: 428–434.

[11] Allison R, Moghissi K, 2013, Photodynamic Therapy Mechanisms. Clinical Endoscopy, 46(1): 24–29.

[12] Henderson T, 2024, Infrared Light Penetration Principles, Practices, and Limitations. Frontiers in Neurology, 15: 1398894.

[13] Cecchetti D, Bauer E, Guerriero E, et al., 2022, Comparative Treatments of a Green Tattoo Ink with Ruby and Nd:YAG Nano- and Picosecond Lasers in Normal and Array Mode. Scientific Reports, 12(1): 3571.

[14] Wu X, Wang X, Shang Y, et al., 2021, Beneficial Effects of Treatment with Low-Fluence 755-nm Q-Switched Alexandrite Laser for Nevus of Ota. Lasers in Surgery and Medicine, 53(10): 1364–1369.

[15] Kauvar A, Sun R, Bhawan J, et al., 2022, Treatment of Facial and Non-Facial Lentigines with a 730 nm Picosecond Titanium-Sapphire Laser is Safe and Effective. Lasers in Surgery and Medicine, 54(1): 89–97.

[16] Shi Y, Jiang W, Li W, et al., 2021, Comparison of Fractionated Frequency-Doubled 1064/532 nm Picosecond Nd:YAG Lasers and Non-Ablative Fractional 1540 nm Er:Glass in Treatment of Facial Atrophic Scars: A Randomized Split-Face Double-Blind Trial. Annals of Translational Medicine, 9(10): 862.

[17] Jacques S, 2013, Optical Properties of Biological Tissues: A Review. Physics in Medicine and Biology, 58(11): R37–R61.

[18] Al-Hadidi N, Griffith J, Al-Jamal M, et al., 2015, Role of Recipient-Site Preparation Techniques and Post-Operative Wound Dressing in Surgical Management of Vitiligo. Journal of Cutaneous and Aesthetic Surgery, 8(2): 79–87.

[19] da Silva T, Ribeiro R, Mencalha A, et al., 2023, Photobiomodulation at Molecular, Cellular, and Systemic Levels. Lasers in Medical Science, 38(1): 136.

[20] Artzi O, Friedman O, Al-Niaimi F, et al., 2020, Mitigation of Postsurgical Scars Using Lasers: A Review. Plastic and Reconstructive Surgery Global Open, 8(4): e2746.

[21] Ge Y, Pan H, Zhao J, et al., 2023, Burn and Wound Repair-Related Research. Chinese Journal of Burns and Wound Repair, 39(1): 53–58.

[22] Yang Z, Yang Z, Zuo Z, 2024, Early Intervention of Carbon Dioxide Fractional Laser in Hypertrophic Scar through TGFβ-1/Smad3 Signaling Pathway. Lasers in Medical Science, 39(1): 78.

[23] Naess E, Molvik T, Ludwig D, et al., 2002, Computer-Assisted Laser Photocoagulation of the Retina: A Hybrid Tracking Approach. Journal of Biomedical Optics, 7(2): 179–189.

[24] Gawęcki M, 2019, Micropulse Laser Treatment of Retinal Diseases. Journal of Clinical Medicine, 8(2): 242.

[25] Luttrull J, Dorin G, 2012, Subthreshold Diode Micropulse Laser Photocoagulation as Invisible Retinal Phototherapy for Diabetic Macular Edema: A Review. Current Diabetes Reviews, 8(4): 274–284.

[26] Liang H, Liang L, Yu Y, et al., 2020, Thermal Effect of Holmium Laser during Ureteroscopic Lithotripsy. BMC Urology, 20(1): 69.