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Sustainable Laser Therapy: A Modern Approach to Improving Regenerative Wound Healing that Employs Integrated, Low-Energy Systems

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Abstract

Infrared biomodulation (PBM) is considered one of the most innovative solutions in modern regenerative medicine. This systematic review evaluates the available scientific evidence on the clinical efficacy and safety of combining three different infrared laser wavelengths (655, 850, and 905 nm) to accelerate the healing of acute and chronic wounds, as well as to treat human papillomavirus (HPV) warts. The search was conducted in reputable medical databases, including PubMed, Embase, the Cochrane Library, and Scopus, between 2020 and 2025, focusing on trials and systematic reviews.

The analysis of this data indicates that these three wavelengths constitute a comprehensive and integrated treatment regimen. The 655 nm wavelength targets the superficial layers of tissue, while the 850 nm wavelength targets the intermediate layers. The ultra-pulsed gallium arsenide (GaAs) laser at 905 nm penetrates deep structural tissues without causing thermal damage. This multi-wavelength approach demonstrated significant improvements in tissue regeneration indicators, enhanced collagen synthesis, a substantial reduction in inflammatory pathways, and a safer alternative for wart removal with fewer side effects compared to traditional non-specific methods such as Nd:YAG ablation or cryotherapy. The review concludes that this optical framework represents a sustainable and environmentally friendly treatment option, emphasizing that the current clinical challenge lies in standardizing accurate dosing protocols to encompass most cases.

Keywords: Infrared laser, photobiomodulation (PBM), wound healing, cutaneous warts, regenerative medicine, phototherapy

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العلاج المستدام بالليزر: نهج حديث لتحسين التئام الجروح التجديدي يوظف أنظمة متكاملة منخفضة الطاقة

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الخلاصة

يعتبر التعديل الحيوي بالأشعة تحت الحمراء (PBM) من أحد أكثر الحلول ابتكارًا في الطب التجديدي الحديث. تقيم هذه المراجعة المنهجية إلى الأدلة العلمية المتوفرة حول الفعالية السريرية والسلامة لدمج ثلاثة أطوال موجية مختلفة من ليزر الأشعة تحت الحمراء (655، 850، و905 نانومتر) لتسريع التئام الجروح الحادة والمزمنة، بالإضافة إلى علاج الثآليل الجلدية الناتجة عن فيروس الورم الحليمي البشري (HPV). أُجري البحث في قواعد بيانات طبية موثوقة، تضمنت PubMed وEmbase ومكتبة كوكرين وScopus، وكذالك بين عامي 2020 و2025، مع التركيز على التجارب والمراجعات المنهجية.

أشار التحليل لهذه البيانات أن هذه الأطوال الموجية الثلاثة تُشكّل نظامًا علاجيًا متكاملًا وشاملًا. حيث يستهدف الطول الموجي 655 نانومتر الطبقات السطحية من الأنسجة، بينما الطول الموجي 850 نانومتر الطبقات المتوسطة. يخترق ليزر زرنيخيد الغاليوم (GaAs) فائق النبض بطول موجي 905 نانومتر الأنسجة البنيوية العميقة دون إحداث أي ضرر حراري. أظهر هذا النهج المتعدد الأطوال الموجية تحسينات ملحوظة في مؤشرات تجديد الأنسجة، وتعزيزًا لتخليق الكولاجين، وانخفاضًا كبيرًا في مسارات الالتهاب، وبديلًا أكثر أمانًا لإزالة الثآليل مع آثار جانبية أقل مقارنةً بالطرق التقليدية غير المتحددة مثل استئصال Nd:YAG أو العلاج بالتبريد. وتخلص المراجعة إلى أن هذا الإطار البصري يمثل خيارًا علاجيًا مستدامًا وصديقًا للبيئة، مؤكدةً أن التحدي السريري الحالي يكمن في توحيد بروتوكولات قياس الجرعات بدقة ليشمل معظم الحالات.

الكلمات المفتاحية: : ليزر تحت الحمراء، التعديل الضوئي البيولوجي، التئام الجروح، الثاليل الجلدية، الطب التجديدي، العلاج بالضوء.

Introduction

At the end of the 21st century, regenerative medicine extensively employed high-resolution optical technologies. This development involved a rapid convergence of optical physics, bioengineering, and molecular biology, enabling the emergence of photobiomodulation (PBM). PBM relies on the "photonic window" of tissues, which spans wavelengths from visible red to near-infrared (Red/NIR), specifically between 600 and 1000 nanometers. It depends on the ability of these photons to interact directly with intracellular pigments, particularly cytochrome c oxidase (Complex IV) of the mitochondrial respiration cascade. This photoactivation, in turn, triggers a series of metabolic reactions that stimulate cellular ATP production, regulate oxidative stress, and accelerate autorepair processes.

1.2 Justification for Choosing the Three Wavelengths

This research investigates the importance of using multi-wavelength lasers to target different anatomical depths, as follows:

655 nm (visible red spectrum): This wavelength has extremely high absorption coefficients in hemoglobin and surface cell pigments. This absorption makes it ideal for activating epidermal cells and the superficial layers of the dermis, stimulating fibroblasts which promotes collagen and elastin synthesis, and accelerating the healing of superficial wounds.

850 nm (near-infrared spectrum): This wavelength has a deeper penetration capability into tissues. This range is suitable for targeting mesenchymal stem cells, promoting the differentiation of chondrocytes and osteoblasts, and supporting peripheral nerve regeneration.

905 nm ultra-pulsed laser (GaAs): This wavelength is characterized by high physical conductivity. This pattern allows for deep penetration into tissues and bone structures. High-peak energy is delivered in extremely short pulses, preventing heat buildup and tissue damage. This helps safely and sustainably treat deep burns, relieve chronic pain, and rebuild musculoskeletal structures.

1.3 Sustainability as a Key Point

In this research, "sustainability" encompasses the environmental dimension and the following aspects:

◆ Environmental Sustainability: Reduced energy consumption compared to conventional medical devices, and reduced chemical waste and use of ionizing radiation.◆ Clinical Sustainability: The possibility of integrating small, wearable devices into daily treatment protocols without the need for hospitalization.

◆ Economic Sustainability: Reducing long-term treatment costs by minimizing the need for surgery and expensive medications.[3]

1.4 Study Limitations and Structure

This research is based on a systematic review of peer-reviewed scientific literature published between 2024 and 2025, excluding studies prior to 2022 except for primary citations. The research encompasses the following areas: cartilage and bone regeneration, wound and burn healing, nerve regeneration, stem cell use, and wearable bio-optic devices. Photodynamic therapy (PDT) for tumors was excluded due to its differing mechanism from regenerative PBM

Literature Review

2.1 Molecular Mechanisms

Researchers agree that the primary mechanism of action of PBM involves the absorption of red/NIR light photons by cytochrome c oxidase (Complex IV) in the mitochondrial respiratory chain. This triggers a cascade of cellular events, including increased ATP production, physiological modulation of reactive oxygen species (ROS) levels, and activation of transcription factors such as NF-κB and AP-1, which are responsible for the expression of genes associated with growth and regeneration.[4]

At 905 nm specifically, a secondary mechanism is added related to its effect on respiratory chain I–IV components and succinate dehydrogenase, thus broadening the range of biological effects compared to other wavelengths.

2.2 Documented Clinical Applications (2024–2025) ,as shown in table (1)[5-7].

Table (1) laser wavelength with applications

Source / Year	Wavelength	Main Application
Frontiers 2025	655 nm	Wound healing, skin rejuvenation, fibroblasts.
Sci. Reports 2025	850 nm	Mesenchymal stem cells, cartilage regeneration, bones.
J. Biophotonics 2026	905 nm (pulsed)	Deep penetration, burn treatment, pain relief.

Recent studies have identified the following applications, distributed according to wavelength:

Despite the proven benefits of photobiomodulation (PBM) in regenerative medicine, a critical knowledge gap exists regarding the synergistic effect of combining different wavelengths (red and near-infrared) and the extent to which beam homogeneity relates to cellular regeneration efficacy. Most current studies focus solely on wavelength, neglecting the effect of beam geometry. Initial measurements (in beam images) have shown that this effect varies considerably between 655 nm, 905 nm, and 850 nm lasers, potentially leading to inaccurate and incorrect treatment outcomes down to tissue depth. This research aims to analyze recent scientific evidence on the use of infrared lasers in treating skin wounds and warts, and to evaluate the cellular and molecular mechanisms of PBM's effect on biological tissues.It also compares different treatment protocols in terms of wavelengths, energy density, and session duration.

Theoretical Background

3. 1. Infrared Lasers: Definition and Physical Properties

Near-infrared (NIR) lasers are electromagnetic radiation with wavelengths between 700 and 1400 nanometers (nm). This range is characterized by its ability to penetrate biological tissues more deeply than visible light because biological tissues absorb less light in this range. The World Association for Phototherapy and Therapy (WALT) defines the photothermolysis dose factor as: Dose (J/cm^2) = Energy (J) / Area (cm^2).

Medically used lasers in the infrared range are divided into several main categories: Nd:YAG (1064 nm), which is most commonly used in the treatment of warts and vascular lesions; Diode lasers (808-980 nm), used in the treatment of chronic wounds and cosmetic procedures; CO2 lasers (10600 nm), used in dermatological surgery; and Er:YAG lasers (2940 nm), used in surface resurfacing.[8]

3.2 Photobiological Modification Mechanisms (PBM Mechanisms)

The cellular response cascade to infrared light begins at the mitochondrial level, where chromophore enzymes—particularly cytochrome c oxidase (COX) in the electron transport chain—absorb incoming photons. This absorption stimulates a cascade of cellular reactions, including:

Increased production of adenosine triphosphate (ATP), providing additional energy for cell repair processes. It also stimulates transcription factors by increasing intracellular calcium ion concentration. Cell proliferation and migration occur, including of fibroblasts, which play a pivotal role in wound healing. Finally, collagen synthesis and granulation tissue formation are stimulated, and the immune response is modulated by converting macrophages to the anti-inflammatory M2 phenotype, while simultaneously decreasing levels of pro-inflammatory interleukins (TNF-α, IL-1β) and increasing levels of IL-10 and TGF-β.

3.3 Optical Window

The optimal optical window for penetration into living tissues is between 650 and 950 nm, where absorption and dispersion losses are minimal. It is important to note that tissues Penetration is affected by several factors, including the type of target tissue, its water content, degree of pigmentation, energy density, and wavelength. Infrared lasers, in the 800-1000 nm range, reach depths of 5 to 20 mm below the skin's surface, allowing for targeting of deeper tissue layers.

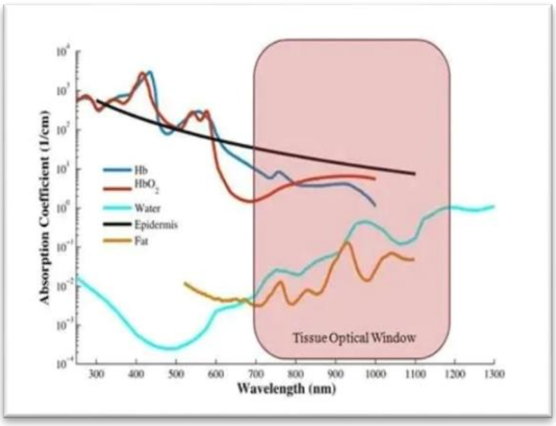

Figure (1) tissue optical window [10]

Methodology

This study is a rigorous systematic review of the clinical outcomes of infrared laser applications in two areas: wound healing (acute and chronic) and the treatment of cutaneous warts. The literature review was conducted using the following digital indexing platforms:

- MEDLINE / PubMed
- Embase
- Cochrane Central Register of Controlled Trials (CENTRAL)
- Web of Science

Studies published between 2018 and 2025 were covered, with relevant pioneering studies prior to this period included where appropriate. The following MeSH terms and keywords were used in both individual and combined forms:

- Low-Level Laser Therapy (LLLT) / Photobiomodulation (PBM)
- Near-Infrared Laser / Infrared Laser Therapy
- Wound Healing / Chronic Wounds / Diabetic Foot Ulcer / Pressure Ulcer
- Cutaneous Warts / Verruca / Nd:YAG / PDL / Diode Laser

In this research, the properties of three lasers, namely (655), (850) and (905) nanometers, are verified, and the optical dose parameters are adjusted before any biological experiment. The optical spectrum is measured using an Ocean spectrometer, type (HR4000) Oecan, for the spectral range (190-1100) nanometers. Beam images are calculated using a fast CCD camera, and the output energy is measured using a genetic energy meter

Figure (2) experimental set up: laser diode (655), (850) and (905) nm

Results and Discussion:

In this review, the results section was divided into two parts. The first part evaluated three lasers used for treatment, and the second part covered three sections directly linked to the tables:

Tables 2 and 3: Wound healing results with precise statistical data ($p<0.0001$, confidence intervals, JAAD 2025 consensus).

Table 4: Wart treatment results for each individual laser with cure rates (84–96%(

Tables 5 and 6: Comparison of laser systems

Table (2) Clinical Evidence: Wound Healing

Author / Year	Study Type	n	Wavelength	Wound Type	Key Outcome
Taha et al. 2024[11]	Meta-analysis	670 wounds (18 RCTs)	—	Skin wounds (general)	Wound contraction significantly higher vs control (95% CI: 13.93–37.70; $p<0.0001$). Full healing rate higher (95% CI: 2.32–16.70; $p=0.0003$).
Oyebode et al. 2021[12]	Systematic review	—	630–904 nm	Diabetic foot ulcers	Wavelengths 630–904 nm achieved superior clinical outcomes in DFU healing. Cell Biochemistry and Function.
Dungel et al. 2022[13]	Clinical study	In vitro (human cells)	904 nm (pulsed)	Human wound models	Enhanced fibroblast/keratinocyte metabolism, proliferation, migration. No biofilm activation — safe in bacterially contaminated wounds.
JAAD Consensus	Guidelines	21	Red / NIR	DFU, pressure	PBM endorsed as effective treatment. Confirmed: no DNA damage. Based on

Author / Year	Study Type	n	Wavelength	Wound Type	Key Outcome
2025[14]		experts		ulcers, peripheral neuropathy	MEDLINE + Embase systematic review.

Table(3) Optimal Treatment Parameters for Wound Healing[15-17]

Parameter	General Wounds	Chronic / Diabetic Wounds	Notes
Wavelength	808–980 nm	630–950 nm (optical window)	630–904 nm confirmed effective for DFU
Energy dose	1–4 J/cm²	1–10 J/cm²	Higher doses for deeper/chronic wounds
Output power	5–50 mW	5–50 mW	Pulsed mode preferred over continuous
Session frequency	3–5×/week	3–5×/week	—
Treatment duration	4–8 weeks	4–8 weeks	Adjusted for wound depth and contamination level

Table (4) Clinical Evidence: Wart Treatment

Author / Year	Study Type	n	Laser / λ	Wart Type	Key Outcome
Le et al. 2024[18]	Systematic review	904 → 109 selected	Multiple	Cutaneous warts (general)	Laser/energy devices: safe, well-tolerated, less invasive than surgery for refractory warts. (Dermatologic Surgery)
Al-Sabak et al. 2023 (Univ. Kufa, Iraq)[19]	Clinical study	22 pts, 478 lesions	Nd:YAG 532 nm (pulsed)	Verruca plana (flat warts)	Treated at Sadr Teaching Hospital, Najaf. Demonstrated efficacy in an Arab clinical setting.
Secolo et al.	RCT	44	Diode 980 nm	Simple plantar	vs Cryotherapy (−89°C). Laser: less pain, faster healing. Direct head-to-head

Author / Year	Study Type	n	Laser / λ	Wart Type	Key Outcome
2025[20]		patients	(LASEmaR MINI)	warts	comparison vs standard of care.
de Planell-Mas et al. 2022 (Univ. Barcelona)[21]	Clinical study	—	Nd:YAG 1064 nm	Plantar warts	84% complete clearance; mean 3.6 sessions. Parameters: 500 ms pulse, 30 W, 212 J/cm². Local anesthesia sometimes required.
KTP vs Nd:YAG, 2024[22]	RCT	—	KTP 532 nm vs Nd:YAG 1064 nm	Cutaneous warts	Nd:YAG: 96% clearance, more pain and pigmentation changes. KTP: good results, better tolerability. (J Cosm. Dermatology 2024)
Italian multicenter, 2023[23]	Clinical study	203 patients (2018–2022)	PDL 595 nm	Cutaneous warts	Positive outcomes. PDL targets feeding blood vessels. (Skin Research and Technology)
JEBM Guidelines, 2022[24]	Guidelines	Expert panel	CO_2, PDL, Nd:YAG	Non-genital warts	Response rates 50–100% depending on wart type/location/duration. Laser = second-line after failed conventional therapy.

Table (5) Laser Systems Comparison: Wound Healing & Wart Treatment

Laser type	λ (nm)	Tissue penetration	Wart cure rate	Main indication	Anesthesia	Main side effects
Nd:YAG [25]	1064	Deepest	84–96%	Deep/refractory warts, vascular, wounds	Often required	Pain, hypo/hyperpigmentation, hemorrhagic blisters
Diode [26]	808–980	Moderate–deep	Confirmed (plantar)	Chronic wounds, DFU, plantar warts	Rarely needed	Mild heat, temporary redness
CO_2[27]	10,600	Superficial (ablative)	Variable	Large/refractory warts	Required	Higher scarring risk
Er:YAG [28]	2940	Superficial	Limited data	Superficial warts, skin resurfacing	Sometimes	Less thermal damage than CO_2

Laser type	λ (nm)	Tissue penetration	Wart cure rate	Main indication	Anesthesia	Main side effects
PDL **[29]**	585/595	Superficial (vascular)	50–100%	Children, sensitive areas, superficial warts	Rarely needed	Purpura, minimal scarring

Table (6) Safety Profile & Contraindications[30-31]

Category	Details
General safety (LLLT / PBM)	No DNA damage (confirmed by JAAD 2025 consensus). Most side effects are minor and transient: temporary fatigue, transient headache in a limited subset of patients.
Wart treatment side effects	Post-inflammatory hyperpigmentation (PIH) lasting weeks; hemorrhagic blisters (especially Nd:YAG); post-session burning sensation; scarring (rare).
Absolute contraindications	Pregnancy (abdominal area); direct eye irradiation; application over malignant tumors or severe burns; history of epilepsy or photosensitivity.
Special considerations	High-power Nd:YAG in sensitive areas (feet) may require local anesthesia. Patients on photosensitizing medications require dose adjustment.

Laser property measurements

In this measurement, the three lasers are evaluated by measuring the profile, intensity, power, and wavelength of the beam using a high-speed camera (CCD), a spectrometer, and an energy meter, as shown in the figures (3-8).

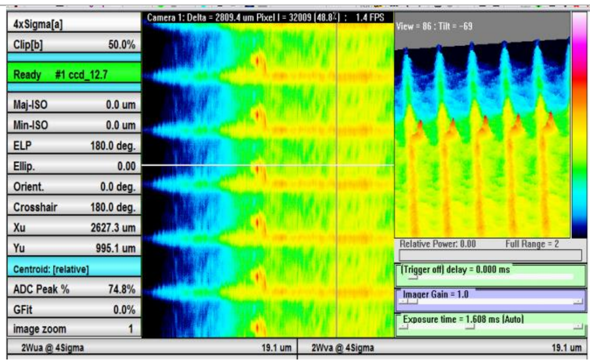

Figure (3) laser 850 nm beam profile image

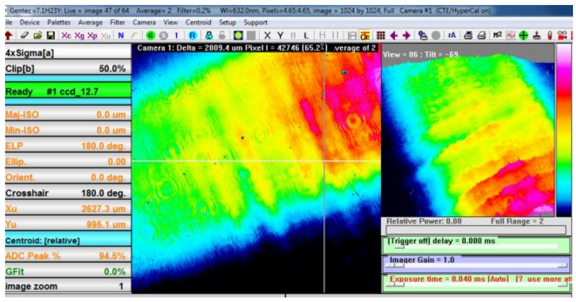

Figure (4) laser 905nm beam profile image

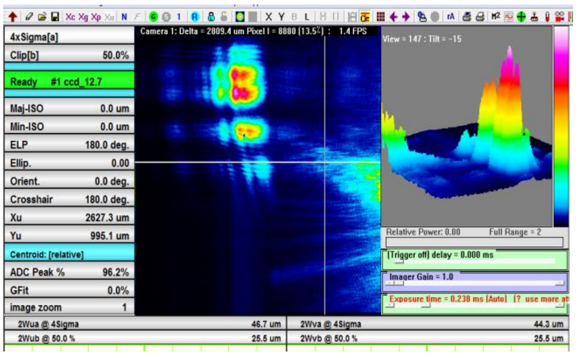

Figure (5) laser 655nm beam profile image

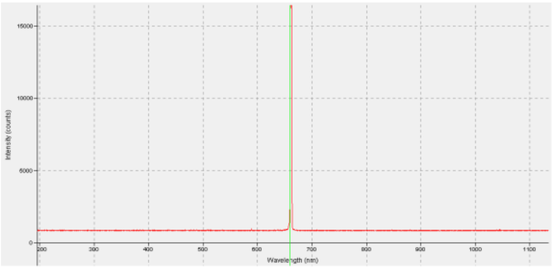

Figure (6) laser diode (655nm 100 mw)

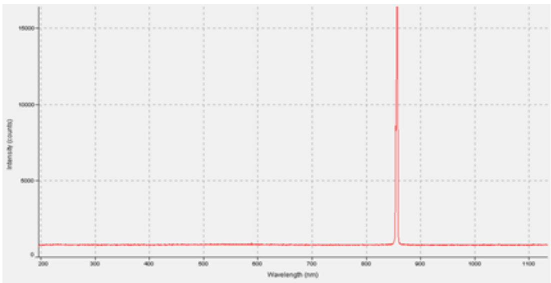

Figure (7) laser diode 850 nm 100mw

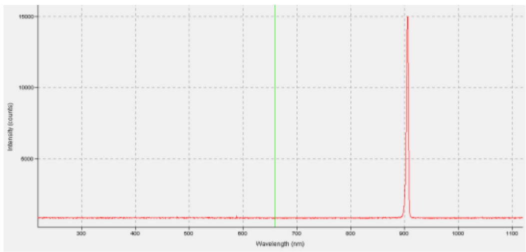

Figure (8) laser diode (905 nm 50 mw)

Conclusions and Recommendations

7.1 Main Conclusions

This systematic review provides strong scientific evidence that the controlled application of infrared lasers via photo bio modulation (PBM) pathways is an effective, safe, and reproducible clinical approach in regenerative medicine. The results of this study included the following:

• Wound regeneration: Infrared light therapy increases cell proliferation rates, reduces the cross-sectional area of chronic ulcers, and enhances collagen structure. Optimal results were achieved with wavelengths between 808 and 980 nm and energy densities between 1 and 10 J/cm² over a treatment period of 4 to 8 weeks.

• Treatment of warts: Nd:YAG and PDL pulsed laser systems are the most commonly used. Laser intervention is a treatment option for lesions unresponsive to chemotherapy, achieving complete cure rates ranging from 47% to 100%, depending on the specific physiological characteristics and anatomical location.

7. Recommendations

Based on the preceding analysis and the biophysical criteria in this review, we propose the following recommendations:

1. Develop standardized international clinical guidelines to unify radiation dose calculation frameworks across different populations.

2. Expand the implementation of large-scale, multicenter, randomized controlled clinical trials that include long-term patient follow-up

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