Photobiomodulation in Dentistry: Current Evidence and Future Directions

Abstract

Photobiomodulation (PBM), also known as low-level laser therapy, is a non-invasive therapeutic approach increasingly utilized in dentistry for pain reduction, inflammation control, and tissue healing. Recent advancements in laser technology have broadened its applications across multiple dental specialties, including periodontics, orthodontics, implantology, and oral surgery, with high patient acceptance due to its non-invasive nature. This review synthesizes current evidence on the biological mechanisms and clinical applications of PBM in dental practice. A comprehensive literature review was conducted to examine the cellular and molecular effects of PBM, alongside its clinical outcomes in pain management, bone healing, soft tissue regeneration, and tooth sensitivity management. Findings indicate that PBM effectively alleviates postoperative and procedural pain, modulates inflammatory responses, and promotes wound healing, thereby enhancing patient comfort. At the cellular level, these effects are mediated by mitochondrial activation, increased adenosine triphosphate production, and regulation of inflammatory mediators. PBM also supports bone regeneration and osseointegration by stimulating cellular proliferation, differentiation, and the activation of redox-sensitive transcription factors involved in osteogenesis. Despite its demonstrated clinical benefits, the absence of standardized treatment protocols limits widespread routine implementation. Future well-designed clinical studies are necessary to optimize PBM parameters and confirm its long-term efficacy in dental practice. Overall, photobiomodulation represents a promising adjunctive therapy that complements conventional dental treatments and contributes to improved patient outcomes.

Keywords

Photobiomodulation, Low-level laser therapy, Dentistry, Pain management, Inflammation, Tissue healing, Bone regeneration, Soft tissue regeneration, Tooth sensitivity, Mitochondrial activation, Osteogenesis, Clinical outcomes, Osseointegration, Redox signaling, Wound healing

1. Introduction

The therapeutic use of light has been documented since ancient times and advanced markedly with the development of laser technology. The development of high power lasers transformed multiple medical and surgical fields, while improvements in light-based devices enabled non-surgical treatments using controlled wavelength and doses.One innovative approach is LLT, also known as low-intensity laser therapy, low-power laser therapy, Photobiostimulation and Photobiomodulation. Photobiomodulation is a non-invasive treatment that uses specific light wavelengths between 650 and 1000mm to promote tissue repair ,reduce inflammation and relieve pain.[1] In dentistry, photobiomodulation is applied at the cellular level to stimulate differentiation, enhance alveolar bone replication, promote soft tissues regeneration and reduce postoperative pain, thereby improving periodontal treatment efficacy and patient comfort.[2] Studies also show it can relieve orthodontic pain and accelerate tooth movement, potentially shortening treatment time. It also promotes bone healing around extraction sites and dental implants by enhancing blood flow and stimulating bone formation.[3,4] In the field of dentistry,Temporomadibular disorders commonly present with pain that affects approximately 10% of adults and impairs quality of life along with physical therapy, numerous studies have provided scientific evidence supporting the use of laser therapy for managing these conditions.[5] Most research has focused on pain reduction and improvements in the mandibular movement. The analgesic and anti-inflammatory effects of low level laser therapy, can reduce pain and muscle sensitivity while improving muscle performance. When combined with speech-language-hearing therapy, it may enhance mandibular movement, improve chewing function and promote balance within the stomatognathic system.[6]Scientific interest in photobiomodulation in dentistry has increased with advances in laser technology, particularly for promoting oral tissues healing,pain control and adjunctive therapeutic procedures. Clinical outcomes demonstrate high patient acceptance due to its noninvasive, atraumatic nature and lack of adverse effects. These advantages, together with rapid recovery and minimal patient cooperation requirements, have supported its expanding use across dental specialties, including in pediatric and special-needs populations.[7]

2. Mechanisms of Action

Photobiomodulation (PBM) also known as Low Level Laser Therapy (LLLT) is a non-invasive way to reduce inflammation and pain thus contributing to enhanced tissue repair. This is achieved by the modulation of cells and tissues to enhance stem cell differentiation and induce cell proliferation. Photobiomodulation (PBM) uses class III, low-level lasers with 500mW output power. Laser and LED light stimulates the cell membrane and mitochondrial photoreceptors synthesis of ATP.[8]

Several theories on mechanisms of action of Photobiomodulation have been proposed:

1. This theory proposes the photochemical interaction with the target cell, the photons from the PBM are absorbed by the chromophores of the mitochondria. Unit IV of the mitochondrial respiratory chain hosts enzyme cytochrome c oxidase which is the primary chromophore which absorbs red light resulting in activity of different signaling molecules like reactive oxygen species (ROS), adenosine triphosphate (ATP), nitric oxide, calcium ions and many others. The enzyme cytochrome c oxidase carries the electrons from the higher energy orbits to the ultimate electron acceptor. This leads to creation of a proton gradient, which increases production of ATP.[8]

2. This theory introduces the direct or indirect photon radiation effects on the genome pool and DNA. PBM produces ROS indirectly, by low laser radiation. ROS is a free radical, and is cytotoxic in high levels, but in low levels, it is beneficial in healing tissues and relieving pain. ROS production is regulated by the mitochondrial membrane potential which is kept in check by the Cyclooxygenase enzymes. ROS helps in proliferation and differentiation of stem cells. ROS with cytokines and growth factors helps in healing the damaged tissues after Low level Laser therapy. This is achieved by moving the satellite cells to the site of injury.[8]

3. This theory is about the light and heat-gated channels. It suggests that there is a heightened activity of the plasma membrane in the red light spectrum (600-810 nm) of laser irradiation, When the wavelength is high and the cytochrome c oxidase is out of range (980-1064 nm).

During the low level radiation, the chromophore is activated when NO is displaced and then bound to the chromophore at the copper and heme centers. The activated chromophore might stop the oxygen supply to cytochrome c oxidase which was producing a large number of ATPs due to increased mitochondrial activity, leading to the shift to oxidative phosphorylation from glycolysis. This leads to increased differentiation of stem cells promoting osteogenesis. ROS produced during PBM also contributes to the cell differentiation. The gated ion channels which are sensitive to light allow Ca2+ to react with NO, cAMP and ROS resulting in activation of transcription factors.[8]

Activation of redox-sensitive transcription factors are triggered by ROS. Factors like NF-kB influence inflammation and bone remodeling by regulating the associated genes. PBM affects the receptor activator of NF-kB Ligand (RANKL) and Osteoprotegerin (OPG) ratio influencing osteogenesis. This ratio was seen elevated with 780 nm wavelength of light in cells derived from human alveolar bone.[9]

3. Clinical Applications in Dentistry

a. Pain Reduction and Analgesia

Photobiomodulation therapy (PBMT) is a rapidly growing non-invasive modality for pain management in dentistry. It involves the use of low-level lasers or light-emitting diode (LED) devices to deliver precise wavelengths of light to target tissues. PBMT modulates nerve function, reduces inflammation, and improves local blood flow, thereby decreasing nociceptive signaling and enhancing patient comfort.[10]

Clinical evidence shows that PBMT effectively reduces pain perception during routine dental procedures such as local anesthetic injections, scaling, and minor oral surgeries. Patients report lower discomfort scores, faster recovery, and reduced need for pharmacologic analgesics. Postoperative pain reduction is attributed to decreased pro-inflammatory cytokines, enhanced ATP production in cells, and improved microcirculation at the surgical site.[11] Figure 1.

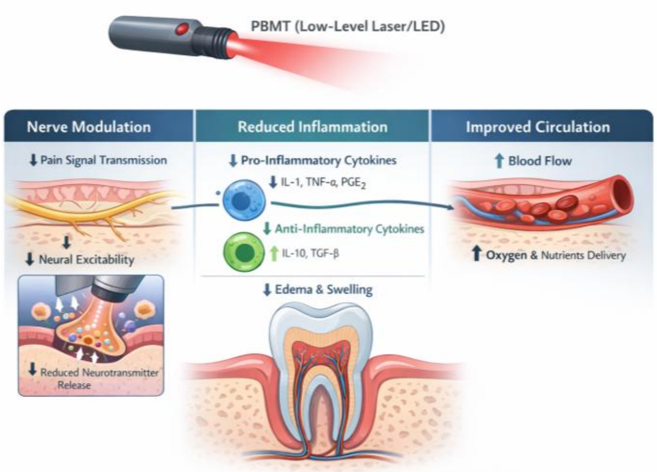

Figure 1. Mechanisms of photobiomodulation-induced analgesia in dental tissues.

Furthermore, PBMT has been evaluated for the management of temporomandibular joint (TMJ) disorders and oral mucositis, showing promising results in reducing chronic pain and inflammation while promoting tissue repair. Standardization of parameters, including wavelength, dose, and exposure time, is critical to ensure reproducible analgesic outcomes.[10,11]

b. Bone Healing and Osseointegration

PBMT significantly contributes to bone regeneration and implant osseointegration by stimulating osteoblastic proliferation, enhancing angiogenesis, and increasing mitochondrial activity in bone cells.[12] Clinical studies report accelerated early-stage implant stabilization and improved bone density in peri-implant regions, indicating faster and more effective osseointegration.[13] Figure 2.

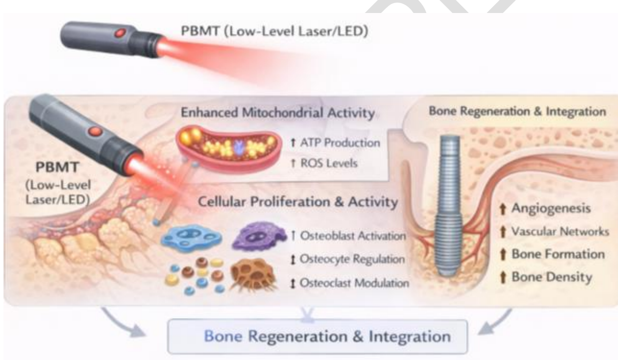

Figure 2. Effect of photobiomodulation on cellular and molecular pathways involved in bone healing and osseointegration.

PBMT also promotes the healing of periapical lesions after endodontic therapy, supporting bone regeneration and reducing inflammatory response.[14] Radiographic studies confirm increased bone fill and improved tissue quality in PBMT-treated sites compared to control groups. When combined with guided bone regeneration (GBR) techniques and biomaterials, PBMT enhances osteoconductive and osteoinductive effects, facilitating graft integration and mineralization.[15] The clinical application of PBMT in regenerative dentistry extends to dental implantology, periodontal therapy, and maxillofacial reconstruction. Optimization of treatment parameters—such as wavelength (typically 600–1000 nm), energy density, irradiation time, and frequency—is essential to maximize therapeutic benefits while avoiding tissue overstimulation.

Emerging research explores the synergistic effects of PBMT with stem cell therapy, growth factors, and bioactive scaffolds, opening new avenues in tissue engineering and regenerative dental medicine.Standardized clinical protocols and large-scale randomized controlled trials are required to establish robust evidence for PBMT's efficacy and long-term outcomes in dental pain management and bone regeneration.[15]

c. Tooth Sensitivity

Tooth sensitivity refers to short, transient and sharp pain response to various factors such as mechanical factors like attrition and abrasion, chemical factors like erosion and biological factors causing gingival recession classified as non-carious cervical lesions of multifactorial etiology.[16]

Apart from that, tooth sensitivity is common adverse effect associated with Dental bleaching procedures, primarily linked to diffusion of hydrogen peroxide through enamel and dentin into pulp leading to acute and transient inflammatory responses like nerve irritation and pulpal inflammation due to release of chemical mediators altering the microcirculation, elevate pressure on peripheral nerve fibers and stimulate nociceptors.[17]

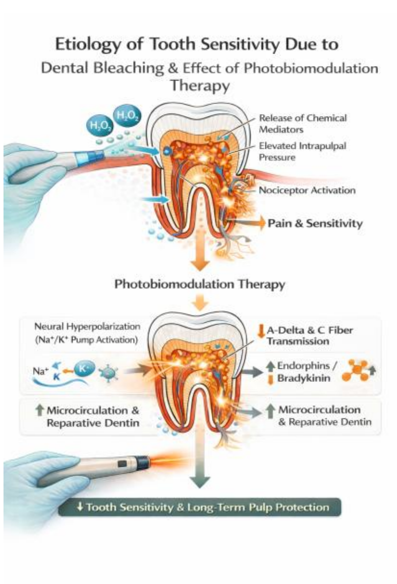

Figure 3. Etiology of Tooth Sensitivity Due to Dental Bleaching & Effect of PBM Therapy

Clinical studies explained different mechanisms of action for treating tooth sensitivity with the use of LLLT such as Neural modulation, Biochemical analgesia, Anti-inflammatory & vascular effects, and Regenerative effectsFigure 3.[16] Clinical application of laser therapy for management of dentin hypersensitivity requires certain parameters to avoid dentin erosion and thermal damage, previous studies have demonstrated power setting above 0.75 W may cause surface charring. However, an ER,CR:YSGG laser operated at 0.25 W ensures safety and efficacy.[18] Beyond its established therapeutic role, PBM has been proposed as prophylactically to minimize sensitivity associated with dental bleaching.

d. Preventive Use of PBM Prior to Bleaching Procedures

While most available studies mostly focused on management of post-bleaching hypersensitivity, the use of PBM as prophylactic before bleaching treatment was proposed as a preventive approach especially with in-office bleaching. The findings suggest that PBM-induced pulp biostimulation is characterized by increased odontoblastic activity and decreased Aδ and C nerve fibers excitability. This approach highlights PBM's potential to improve patient comfort during aesthetic dental treatments.[19]

Although many studies illustrate the positive role of PBM in reducing dentin sensitivity, treatment efficacy depends on various parameters such as site, wavelength, power density, absorption rate and exposure time.

Despite these encouraging findings, inconsistencies in laser parameters and treatment protocols across studies require further high-quality randomized clinical trials to establish clinical guidelines.

e. Tissue regeneration and Healing

Photobiomodulation (PBM), also known as low-level laser therapy (LLLT), is a non-invasive therapeutic approach that enhances tissue regeneration and wound healing regulating cellular and molecular processes rather than producing thermal effects [Figure 4]. When delivered within optimal therapeutic wavelengths, PBM initiates photochemical reactions that activate biological processes without causing structural damage to tissues which leads to regulated inflammation control, enhanced extracellular matrix formation, and improved cellular survival during wound healing.[20,22]

f. PBM in soft tissue healing and Stem cell modulation

Furthermore, the use of PBM in periodontal and mucogingival therapy is supported by its ability to promote soft tissue healing, reflecting clinical outcomes including reduced postoperative inflammation, decreasing pain level and improving esthetic outcomes.[22,23] [Figure 4]. Beyond soft tissue healing, PBM has also attracted significant interest in regenerative endodontics, PBM has demonstrated great potential in stem cells modulation and intracellular signaling in regeneration of pulp-dentin complexes. Lower doses of low-level laser therapy are associated with more efficacy in enhancing stem cell proliferation .[21] Figure 4.

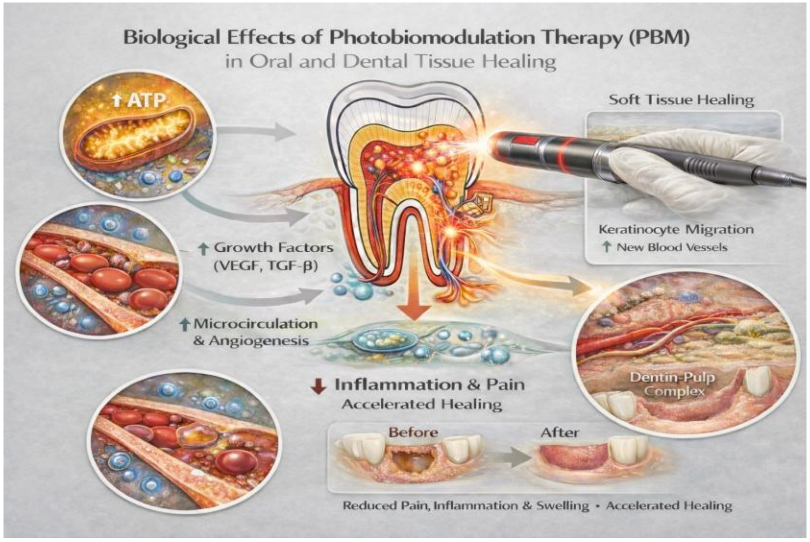

Figure 4. Biological Actions of PBM in Dental Tissues

g. Management of Alveolar Osteitis using LLLT

PBM also showed great results in management of alveolar osteitis. Alveolar osteitis, also known as Dry socket, is a post-operative complication marked by intense pain, dislodgement of blood clot and delayed wound healing of the socket. LLLT enhances wound healing by promoting immune cell migration, stimulating soft tissue repair and increasing blood flow. PBM shows greater outcomes compared to conventional treatments such as Alveogyl during follow-up.[24] [Figure 2].

Despite substantial evidence supporting the regenerative benefits of PBM in dental application, its clinical implementation remains restricted due to various challenges. The most critical limitation is the absence of standardized treatment protocols and guidelines along with variability in laser wavelength and parameters, which compromises outcome reliability and results comparability.

Future research is needed to establish evidence-based protocols and parameters conducting high-quality randomized controlled trials to confirm long term safety and efficacy.

4. Upcoming Trends and Future Directions

a. Home-Based Photobiomodulation Devices

Many photobiomodulation (PBM) devices are currently available on the market for home use, particularly for the treatment of inflammation, pain relief, recurrent herpetic infections, and as supportive therapy following clinical procedures. The availability of these devices may add value to conventional clinical tools by extending therapy beyond the dental office. However, further research is still required to establish robust evidence-based databases that address dosimetric accuracy, patient compliance, and safety monitoring, as variability in wavelength, irradiance, and exposure time remains a significant concern.[25]

b. PBM Combined with Platelet Concentrates (PRP/PRF)

Platelet-rich plasma (PRP) and platelet-rich fibrin (PRF) provide concentrated growth factors that enhance tissue healing. The use of PBM in combination with platelet concentrates may further stimulate growth factor activity, cellular proliferation, and tissue remodeling when applied alongside autologous biologics. Future research is expected to focus on optimizing combined treatment protocols and identifying clinical scenarios in which this synergistic approach offers the greatest therapeutic benefit.[26]

c. PBM and Dental Pulp Mesenchymal Stem Cells

Emerging evidence indicates that PBM can modulate the proliferation and differentiation of dental pulp mesenchymal stem cells, promoting osteogenic and odontogenic pathways. This interaction suggests a potential role for PBM in regenerative endodontics and tissue engineering. Future investigations will likely explore dose-dependent effects and translational applications related to pulp regeneration and dentin repair.[27]

d. PBM in Orthodontics, Temporomandibular Disorders, and Oral Surgery

PBM has demonstrated consistent benefits in postoperative pain control and enhancement of healing following oral surgical procedures. However, evidence supporting its role in accelerating orthodontic tooth movement remains variable. Ongoing and future research aims to clarify its effectiveness in orthodontics and to establish standardized protocols for tooth movement acceleration and temporomandibular disorder management.[28]

e. Inflammation Control and Soft Tissue Healing

One of the most established applications of PBM is its ability to modulate inflammation and promote soft tissue healing. Through immunomodulatory and bioenergetic mechanisms, PBM supports wound repair and reduces postoperative morbidity. Future clinical integration may expand the use of PBM as a host-modulating adjunct in periodontal therapy and implant-related procedures.[29]

f. PBM in Oral Oncology and Supportive Cancer Care

PBM has gained strong clinical support for the prevention and management of oncotherapy-associated oral mucositis. Its inclusion in international clinical guidelines highlights its growing role in supportive cancer care. Future research is expected to refine dosing protocols, explore additional supportive oncologic applications, and facilitate broader clinical adoption.[30]

g. PBM in Implant Dentistry and Peri-Implant Disease

PBM is increasingly explored as an adjunctive therapy in implant dentistry to enhance soft tissue healing and modulating peri-implant inflammation. Its non-thermal and non-destructive nature makes it particularly attractive for managing peri-implant conditions. Future studies may further clarify its role in supporting osseointegration and in antibiotic-sparing management of peri-implantitis.[31]

Overall, photobiomodulation remains an actively evolving field in dentistry, with ongoing preclinical and clinical research continuously expanding its therapeutic indications and refining its clinical protocols.

5. Conclusion

In the Conclusion,Photobiomodulation is emerging as a promising alternative to conventional pain management in dentistry, with both lasers and light-emitting diodes showing potential for pain relief in dentistry and the other physical therapy but variability in study methods and treatment parameters limit its routine clinical use.Furthermore, we observe that more studies is needed before introducing the photobiomodulation in the clinical practise even in the routine dental extraction procedure.

Abbreviations:

PBM – Photobiomodulation

PBMT – Photobiomodulation Therapy

LLLT – Low-Level Laser Therapy

LED – Light-Emitting Diode

ATP – Adenosine Triphosphate

ROS – Reactive Oxygen Species

NF-κB – Nuclear Factor Kappa B

AP-1 – Activator Protein-1

VEGF – Vascular Endothelial Growth Factor

HIF-1α – Hypoxia-Inducible Factor-1 Alpha

TGF-β – Transforming Growth Factor Beta

NO – Nitric Oxide

Ca^{2+} – Calcium Ion

cAMP – Cyclic Adenosine Monophosphate

RANKL – Receptor Activator of Nuclear Factor Kappa B Ligand

OPG – Osteoprotegerin

TMJ – Temporomandibular Joint

GBR – Guided Bone Regeneration

PRP – Platelet-Rich Plasma

PRF – Platelet-Rich Fibrin

VAS – Visual Analog Scale

GaAlAs – Gallium–Aluminum–Arsenide Laser

ER,Cr:YSGG – Erbium, Chromium-doped Yttrium Scandium Gallium Garnet Laser

MASCC/ISOO – Multinational Association of Supportive Care in Cancer / International Society of Oral Oncology

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