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RESEARCH ARTICLE

The effects and mechanisms of photobiomodulation (PBM) therapy in accelerating orthodontic tooth movement: Immerse in intricacy. A Review

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Abstract: **Background :** Photobiomodulation (PBM), previously referred to as low-level laser therapy (LLLT), has developed into a non-invasive and biologically based complement in orthodontic practice. Utilising low-intensity light within the red to near-infrared spectrum, PBM has shown potential in expediting orthodontic tooth movement, alleviating treatment-related discomfort, and promoting tissue repair. **Objective:** This review aims to comprehensively analyze current human and experimental evidence regarding the efficacy, mechanisms, parameters, and clinical applications of PBM in orthodontics, while highlighting its advantages, limitations, and future prospects. **Methods :** A systematic literature search was conducted using PubMed, Scopus, and Google Scholar databases for studies published up to 2025. Clinical trials, in vitro and in vivo studies, and systematic reviews investigating PBM for orthodontic purposes were included. Key variables such as wavelength, energy density, application mode, and biological outcomes were extracted and compared. **Results :** Numerous clinical and preclinical studies report that PBM accelerates orthodontic tooth movement by modulating mitochondrial function, increasing cytokine activity (e.g., IL-1β, RANKL), and enhancing bone remodeling. Wavelengths between 630 and 940 nm have shown efficacy. While lasers and LEDs are used, intraoral LED devices offer greater practicality for daily use. Pain reduction and soft tissue healing benefits have also been consistently reported. However, inconsistencies in PBM parameters, treatment intervals, and study designs limit direct comparability and standardization. **Conclusion :** Photobiomodulation represents a promising adjunctive tool in orthodontics, capable of enhancing treatment efficiency and patient comfort. Despite encouraging outcomes, standardized protocols and long-term multicenter trials are needed to fully establish its clinical utility and optimize therapeutic parameters

Keywords: Low level laser therapy, Orthodontic tooth movement, Photobiomodulation.

INTRODUCTION

Malocclusion affects up to 56% of the global population, leading to various dental and aesthetic issues (1). Malocclusion includes misalignment of teeth and jaws (2). Orthodontic treatment is the primary solution, but the prolonged duration of orthodontic treatment, typically lasting 2–3 years, often acts as a primary obstacle for patients to accept conventional methods (3). Complications can include root resorption, dental caries, and increased pain levels (4). Dental professionals have spent a great deal of time and energy investigating potential ways to shorten the duration of treatment while simultaneously speeding up the movement of teeth. Numerous new approaches, both invasive and noninvasive, have been developed and implemented thus far (5, 6). Because intrusive techniques can cause discomfort and pain for patients, orthodontists are seeking a non-invasive and user-friendly approach (5).

Photobiomodulation (PBM), a noninvasive technique, has been employed as a potential method to expedite orthodontic tooth movement (7). This technology employs two light sources with differing coherence to elicit a biological response: low-level lasers (LLLs) as coherent light and light-emitting diodes (LEDs) as incoherent light (5).

This review will be highlighted under the following headings.

Orthodontic Tooth Movement (OTM) and Its Biological Basis

The biomechanical process of orthodontic tooth movement involves applying controlled mechanical stresses to teeth, which remodels the periodontal ligament (PDL) and alveolar bone around the teeth. Application of force to a tooth generates pressure and tension zones within the periodontal ligament (PDL). The process triggers a series of biological responses through mechanotransduction, converting mechanical stress on the tension side. This coordinated process of bone remodelling facilitates the movement of the tooth within the alveolar socket. The process is governed by various biochemical mediators, including interleukins (IL-1β and IL-6), tumour necrosis factor-alpha (TNF-α), prostaglandins (e.g., PGE2), and signaling molecules such as RANK/RANKL/OPG (8).

The efficiency and speed of tooth movement are influenced by individual biological variability, the magnitude of force applied, and the inflammatory and reparative responses of the tissue. These biological processes serve as the basis for treatment approaches, such as photobiomodulation (PBM), that try to safely and predictably accelerate or modify orthodontic tooth movement.

Photobiomodulation (PBM) Therapy Overview

Photobiomodulation (PBM), also known as Low-Level Laser/Light Therapy (LLLT) or Light Accelerated Orthodontics (LAO) (9), is an innovative noninvasive method in orthodontics that has been shown to expedite orthodontic tooth movement (10). It has gained popularity due to its non-invasive and painless nature (11). Photobiomodulation (PBM) involves the application of visible light in the near-infrared (NIR) spectrum to promote tissue repair (12). According to the wavelength of light. Light can be categorized into ultraviolet radiation, visible light (VL), and infrared (IR) based on its wavelengths. The visible light spectrum can be categorized into red light (625–700 nm), orange light (590–625 nm), yellow light (565–590 nm), green light (500–565 nm), and violet/blue light (400–500 nm). Infrared (IR) radiation comprises near-infrared (NIR) wavelengths ranging from 700 to 1440 nm, mid-infrared (mid-IR) wavelengths from 1440 to 3000 nm, and far-infrared (far-IR) wavelengths from 3000 nm to 1 mm (13). The effectiveness of PBM on target tissue is contingent upon various parameters, including light source, wavelength, energy density, pulse mode, and duration of application (14). Nonetheless, the penetration of red and near-infrared light is superior to that of other wavelengths (11, 15). NIR light can suppress light scattering, resulting in reduced attenuation during tissue propagation (16, 17). PBM therapy has increasingly gained prominence in the fields of medicine and dentistry. It has been utilised in dermatology, neurotology, and neuroprotection for over 18 to 55 years (18-23). For over 36 years, PBM therapy has been enhancing bone metabolism and the regeneration process (24) and has been employed in diverse clinical applications in dentistry for over 37 years, including craniofacial wound healing, dentine hypersensitivity, and oral mucosa mucositis, and it exhibits analgesic properties, among other uses (25-31). Recent reviews have concentrated on the role of PBM therapy and its extensive clinical applications (32, 33). Nevertheless, limited discourse regarding the role of PBM therapy in orthodontics is available (34, 35). Jimenez-Peña OM et al (36), summarizes six systematic reviews (all positive on acceleration) but highlights high heterogeneity in protocols. Gonçalves A et al. (37), in his reviews, covers 69 studies according to PRISMA guidelines. Confirms PBM's role in enhancing movement rate and reducing pain. Perim Rosa E et al. (38), in the review article, interpreted that photobiomodulation increases uprighting tooth movement and modulates IL-1β expression during orthodontic bone remodelling and also highlights mechanistic evidence linking PBM to inflammatory cytokine modulation and targeted tooth movement efficiency. Baharami et al. (39), in their systematic review of LED-mediated PBM, focus on LED devices, confirming their non-invasive, practical home-use potential in facilitating tooth movement (Table 1). The efficacy of PBM therapy as an adjunctive treatment in orthodontics remains inadequately clarified; therefore, this study seeks to explore the potential advantages of PBM therapy in this field.

Table1.Recent review articles published on Photobiomodulation therapy.

YEAR	AUTHOR	REVIEW TYPE	FOCUS	KEY FINDINGS
2024-2025	Jimenez-Pena OM et al.	Umbrella review	Laser PBM for tooth movement acceleration	Positive trends; high protocol heterogeneity; recommends dose standardization
2024	Goncalves A et al.	Systematic (clinical/preclinical)	Wavelength efficacy & mechanisms	Effective wavelengths and protocol clarity; pain & movement benefits
2023-2025	Perim Rosa E et al.	Mechanistic clinical	Tooth uprighting & cytokines	IL-1β modulation in targeted movement

2025	Bahrami et al	Systematic (LED focus	LED-PBM in tooth movement	Validates at-home LED applications

Mechanisms of PBM Therapy in Orthodontics

The biological effects of PBM are primarily mediated by photon absorption by cytochrome c oxidase (CCO), a terminal enzyme located in the fourth unit of the mitochondrial respiratory chain complex. This absorption causes enhanced ATP generation, which cellular energy and metabolic activity; the release of nitric oxide (NO), which promotes vasodilation and improves blood flow; and the control of reactive oxygen species (ROS), which regulates inflammation and cellular signaling. Transcription factor activation stimulates the production of genes involved in bone repair, regeneration, and remodeling (Figure-1).

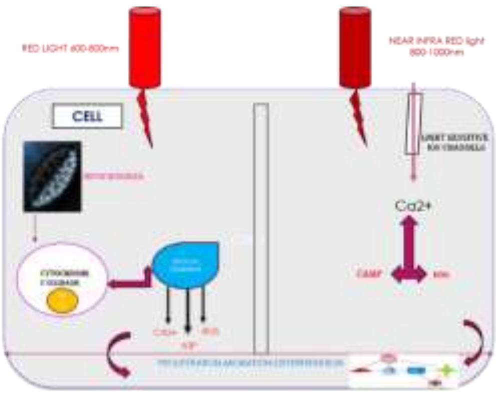

Figure1.Mechanisim of Photobiomodulation

In the context of orthodontic therapy, these effects lead to accelerated recruitment of osteoclasts and osteoblasts. Augmented remodelling of the alveolar bone through manipulation of inflammatory cytokines (e.g., IL-1β, IL-6, TNF-α) Enhanced turnover of the periodontal ligament (PDL).

According to one of the hypotheses, it has been found that laser irradiation in the red light spectrum enhances activity in the plasma membrane of cells (14). Biochemical activity is minimal within the wavelength range of 700–770 nm. The optimal wavelength for treatment is typically regarded as 810 nm (40). Wavelengths extending to 950 nm are required to penetrate cutaneous tissue and reach deeper layers. Wang et al. indicate that the chromophore cytochrome c oxidase, along with other chromophores, can absorb 810 nm light to enhance mitochondrial activity (41). The primary chromophore exhibits two bands, resulting in a range of 600–810 nm.

Cytochrome c oxidase serves as the primary chromophore for red light absorption; however, other molecules are believed to absorb higher wavelengths beyond the range of cytochrome c oxidase (42). This theory involves light and heat-gated channels, particularly members of the transient receptor potential (TRP) family, which absorb photons in the range of 980–1064 nm (18). A theory regarding the mechanism of cytochrome c oxidase suggests that inhibitory nitric oxide (NO) is displaced by irradiation, subsequently binding to the copper and heme centers of the chromophore to facilitate its activation. The activity of cytochrome c oxidase enhances mitochondrial function, resulting in increased ATP production. Alternatively, the chromophore's activity may inhibit oxygen's access to the active site of cytochrome c oxidase (18).

The proliferation and differentiation of stem cells are enhanced, likely due to a shift in priorities within the ATP-rich cell, which is transitioning from glycolysis to oxidative phosphorylation. This phenomenon can be regarded as a metabolic switch, which is a recognized key factor in osteogenesis. Other by-products of PBM, particularly ROS, are linked to improved differentiation, leading to a series of subsequent actions (Figure 1). One secondary action involves Ca^{2+} entering cells through light-sensitive gated ion channels, leading to interactions with reactive oxygen species (ROS), nitric oxide (NO), and cyclic AMP (cAMP), subsequently influencing the activity of transcription factors (43).

Efficacy of PBM Therapy in Animal Studies

Orthodontic treatment involves the application of specific forces that can modify tooth positioning and initiate various biological responses (44). This undergoes bone remodelling with bone resorption and deposition, bringing tooth movement, which enhances support for the teeth in its targeted location (45). Numerous studies demonstrate the efficacy of PBM therapy in animal models, showing significant improvements in OTM rates and reduced complications.

An optimal window with a wavelength range of 660 nm to 830 nm is recognized as the most frequently utilised in PBM therapy within orthodontics.

A study by Suzuki et al. (46) showed that in the PBM therapy group, there was more bone growth on the tension side and more bone loss on the compression side compared to the control group. Additionally, a significant increase in OTM distance and a reduction in hyalinization area were observed in the PBM therapy group, suggesting that 810 nm NIR light facilitates bone remodelling in orthodontics. Keklikci HB (47) showed in his study that LLLT with a 650 nm wavelength increases orthodontic tooth movement in rats using 405, 532, 650, and 940 nm wavelengths of low-level laser therapies.

He also conducted a comparison of the effects of 405 nm, 532 nm, 650 nm, and 940 nm light on OIIRR (Orthodontically induced root resorption). The results indicated that all wavelengths were effective in inhibiting root resorption and reducing the number of lacunae, with the exception of 405 nm light, which was limited by its penetration depth in tissue (48).

Jawad et al., according to the results of their in vitro study with the laser at 940 nm wavelength, stated there was an increased ALP activity in the laser-applied group compared to the control group. They reported that LLLT at a 940 nm wavelength can contribute to bone formation by stimulating osteoblast cells (49). Yang et al. (50) demonstrated that both 660 nm and 830 nm light can stimulate the expression of IL-1 (Interleukin-1), RANKL (Receptor Activator of Nuclear Factor Kappa-B Ligand), and OPG (Osteoprotegerin). The 660 nm light demonstrated superior efficacy in promoting bone remodelling compared to the 830 nm light during the initial phase of orthodontic treatment. Wu et al. (51) demonstrated that PBM therapy at a wavelength of 1064 nm with a dose of 8 J/cm² inhibits osteogenesis in human periodontal ligament stem cells (hPDLSCs), whereas improved proliferation and osteogenic capacity are observed at doses of 2–6 J/cm².

Cell proliferation was observed to be more effective at aDose of 4 J/cm², while enhanced osteogenesis was noted at 6 J/cm². These studies suggest that the relationship between wavelength and fluence is crucial. If the target is CCO, it is well accepted that red light (630 to 670 nm) or near-infrared light (740 to 940 nm) will have positive effects, using fluences in the stimulatory range of 3 to 10 J⁄cm². The Arndt–Schultz law states that effective biological responses occur exclusively within a therapeutic window (52), aligning with the observation that lower doses are advantageous while higher doses are harmful in PBM therapy

The underlying reason for the phenomenon may be attributed to varying energy densities that potentially regulate distinct differentiation-related signaling pathways, influencing osteocyte and osteoclast activity (53). Different parameters in PBM therapy may be selected based on specific clinical settings, necessitating further studies to evaluate the effectiveness of PBM therapy and optimize its parameters.

Efficacy of PBM therapy on Human studies

Numerous clinical studies in humans have shown that photobiomodulation (PBM) effectively accelerates orthodontic tooth movement and alleviates discomfort associated with treatment. Photobiomodulation (PBM), utilising laser and LED sources, stimulates mitochondrial activity, enhances ATP production, and modulates inflammatory mediators, thus facilitating accelerated bone remodelling during orthodontic tooth movement (54, 55). Cruz et al. (56) reported an approximately 30% enhancement in the rate of canine retraction using 780 nm diode laser therapy in a randomized controlled experiment compared to the control group. Kau et al (57), observed a substantial decrease in treatment duration during alignment stages utilising an intraoral LED device at 850 nm (Orthopulse®). Doshi-Mehta and Bhad-Patil (58) confirmed the clinical efficacy of 810 nm laser therapy in promoting anterior alignment and reducing pain perception.

Nonetheless, some studies have yielded inconsistent findings. Sandler et al. (59) conducted a multicenter RCT utilising an 808 nm diode laser and found no statistically significant difference in the rate of tooth movement when compared to controls. This underscores the variability in individual responses and the influence of heterogeneity in PBM protocols. A systematic review conducted by Domínguez et al. (60), which analysed 17 human randomized controlled trials (RCTs), concluded that although most studies reported beneficial effects of photobiomodulation (PBM), the absence of standardized parameters—such as wavelength, energy density, and application frequency—restricts direct comparability among the studies. Another meta-analysis by Huang et al. (61) corroborated that PBM is a safe and effective adjunct for accelerating orthodontic treatment, provided that dosimetry is meticulously optimized.

Besides facilitating tooth mobility, PBM has been shown to be effective in alleviating orthodontic pain and promoting soft tissue recovery. Qamruddin et al. (62) documented markedly reduced pain scores in patients treated with PBM in their systematic evaluation of randomized studies. Human clinical studies collectively endorse the use of PBM as a promising adjunct in orthodontics; however, additional well-controlled trials with standardized protocols are necessary to more firmly ascertain its clinical efficacy.

Optimal Wavelengths and Dosages for PBM Therapy

Baxter et al. (63) stated that laser wavelength and energy density are the most important factors determining the tissue response. The most critical characteristics in PBM are power density (irradiance), measured in mW/cm², and energy density (fluence), measured in J/cm². A multitude of the studies examined here, and indeed the majority of the scientific literature, have fundamentally wrong assertions regarding laser output in watts. To fully describe a particular PBM technique, it is essential to describe numerous factors, including wavelength, fluence, power density, pulse shape, and time. The selection of these parameters must be tailored to each patient. An error in parameter selection for each patient may result in an ineffective or detrimental therapeutic outcome. Different wavelengths and dosages of PBM therapy yield varying effects on bone remodeling and cellular responses (18). Wavelengths of 650 nm and 940 nm show better osteogenic abilities compared to others (19). High doses (5-8 J/cm²) can inhibit cellular functions, while low doses (1-4 J/cm²) promote osteogenesis (20). The therapeutic window is crucial for achieving positive biological responses.

The Arndt-Schultz law of biphasic dosage response is a representation of this idea, and it has become the central notion of PBM. Nevertheless, there is a lack of consensus regarding the suitable range of fluence and irradiance values that trigger these notable changes (Figure 2). Multiple studies indicate that fluences between 3 and 10 J/cm² at the cellular level will effectively stimulate metabolic activity (64). Although numerous research studies have demonstrated a beneficial effect of PBM (65-67), several have failed to provide any advantage (68, 69), and some reports have even revealed adverse results under what are purported to be identical irradiation conditions as those in positive trials.

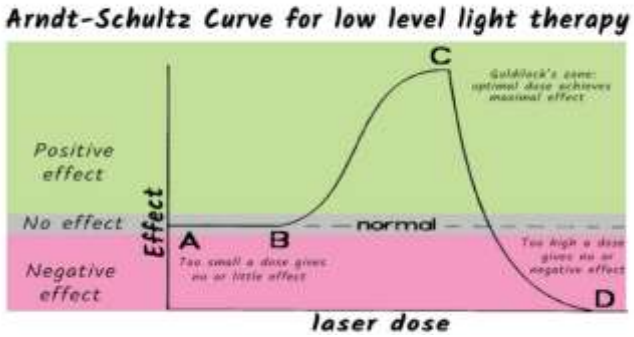

Figure 2. Arndt-Schultz Law representing Bi-phasic response

There is evidence to suggest that there is a dose threshold that must be reached in order for PBM to have any influence on biological processes (70). In the event that this is the case, the power density tought to be sufficiently high to reach the depth of the cellular components that are accountable for tooth change (71). It is possible that the effect of PBM could be negatively affected by dosages that are excessive (72). High doses of laser therapy were shown to slow down the pace of tooth movement in dogs, according to the findings of Goulart et al. (73), while lesser doses of laser therapy were found to have the opposite effect.

Although the ideal dosage is still unknown, a systematic analysis revealed that diode lasers with energy densities of 2.5, 5, and 8 J/cm² were more effective than those with energy densities of 20 and 25 J/cm². Jiménez-Peña OM et al. (2025) Summarizes, all positive on acceleration but recommends standardized dosimetry: ≥ twice/month, 4–10 irradiation points, 3–50 s per point, 20–150 mW power, and ~5.3 J/cm² energy density at 780–810 nm. Gonçalves A et al., in his reviews, identifies effective wavelengths (≈ 640 ± 25, 830 ± 20, 960 ± 20 nm) with ≥5 J/cm² daily or alternate-day sessions.

Concerning the fundamental cause of the phenomena, we can only hypothesize that varying energy densities may modulate distinct differentiation-related signaling pathways that influence osteocyte and osteoclast activity (74). Nonetheless, various parameters of PBM therapy may be precisely determined for distinct clinical contexts, and additional research is necessary to evaluate the efficacy of PBM therapy and refine its parameters.

Future Directions for PBM Therapy in Orthodontics

Despite its growing acceptance, the exact mechanisms and full efficacy of PBM therapy in orthodontics require further investigation. More comprehensive studies are needed to optimize treatment parameters. Future research should focus on clinical applications and long-term outcomes of PBM therapy.

Despite the intriguing potential of photobiomodulation (PBM) in expediting orthodontic tooth movement, alleviating pain, and promoting tissue repair, numerous aspects remain inadequately investigated and require further research. The forthcoming objectives are to enhance the clinical usefulness, mechanistic comprehension, and standardization of PBM in orthodontics.

1. Standardization of PBM Protocols

Current clinical studies employ a diverse array of parameters, encompassing different wavelengths (630–980 nm), power densities, exposure durations, and irradiation frequencies. Future research must prioritize the development of standardized, evidence-based PBM protocols, as well as the definition of the optimal therapeutic window for various orthodontic stages (e.g., alignment versus retraction) and tissue types.

2. Personalized PBM Therapy

Considering individual differences in biological response, tailored PBM regimens that account for age, bone density, metabolic rate, and genetic markers could enhance treatment efficacy. Investigating biomarker-guided PBM dosing through salivary or GCF cytokines such as IL-1β, IL-6, or RANKL may facilitate the customization of therapy according to individual biological responses.

3. Integration with Digital Orthodontics

The future of orthodontics is rooted in digital technologies, including 3D imaging, intraoral scanners, and AI-driven treatment planning. The integration of PBM protocols into digital orthodontic workflows, such as CAD/CAM-guided light delivery devices, may improve precision and predictability in treatment timing and outcomes.

4. Development of Smart and Wearable PBM Devices

The development of intraoral LED-based PBM devices, such as OrthoPulse®, facilitates at-home therapy. Future innovations may encompass smart wearable PBM systems that provide real-time feedback, dose tracking, and app-based monitoring to enhance patient compliance and ensure consistent therapy delivery.

5. Long-Term Clinical Studies

Current research predominantly emphasizes short-term studies centered on initial tooth movement. Future clinical trials should examine the long-term stability of accelerated movement, the risks of root resorption, gingival and periodontal health, and safety outcomes associated with chronic PBM exposure. Additionally, multicenter randomized controlled trials (RCTs) with larger samples and diverse populations are necessary to validate the widespread clinical adoption of PBM.

6. Mechanistic and Molecular Research

Additional in vivo and in vitro studies are required to clarify the specific molecular mechanisms by which PBM influences osteoclastic and osteoblastic activity, angiogenesis, and neural signaling related to pain modulation. This may facilitate the identification of dose-dependent thresholds for particular biological effects and therapeutic applications.

7. Expanded Clinical Applications

PBM may have expanded applications in orthodontics beyond the facilitation of tooth movement. Improving mini-implant stability, addressing orthodontic pain and ulcers, facilitating bone healing following extractions or corticotomy, and aiding in retention phase remodelling. Future research should systematically evaluate these adjunctive applications.

CONCLUSION

Photobiomodulation integrates biomedicine and technology, presenting promising opportunities for the improvement of orthodontic treatments. Advancements in dosimetry, delivery systems, and personalized care position PBM as a potential integral component of evidence-based orthodontic practice. Investments in standardization, personalization, and digital integration are essential for maximizing clinical utility

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