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SPECIAL ISSUE RESEARCH ARTICLE

Enhancing bone remodeling and accelerating tooth movement with photobiomodulation in middle-aged adults

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Abstract
Although age is not a contraindication for orthodontic treatment, it can be considered more challenging in mature adult patients, mainly due to a less responsive bone metabolism and reduced osteoblastic activity compared to young patients. In orthodontics, photobiomodulation (PBM) has shown positive results in bone remodeling during tooth movement. This study seeks to assess the effect of PBM can have a positive effect on bone remodeling, stimulating bone formation in middle-aged individuals and allowing for a better periodontal condition. Bone structure and the length of the roots were evaluated using cone beam computed tomography images before and after tooth movement and PBM in patients aged between 40 and 60 years. In addition, we aimed to evaluate the expression of the markers receptor activator of NFκB (RANK), osteoprotegerin (OPG), and osteopontin (OPN) presented in the crevicular fluid using the enzyme-linked immunosorbent assay test. Tooth movement was performed by intruding upper molars with two mini-implants as anchorage bilaterally. One side received PBM with light-emitting diode (LED) light and the contralateral side was used as control (no irradiation). The PBM equipment specially designed for this study consisted of six LEDs of 5 mW each, for 7 minutes, totaling 2 J, 3 times a week, for 5 months. The PMB group showed greater tooth movement ($p < 0.05$), an increase of 74% on average for bone height. PBM induced a significant increase in RANK expression at month 3 ($p < 0.05$), and the expression of OPG and OPN showed a significant increase in the fifth month of movement ($p < 0.05$) in the PBM group. PBM may represent an adjunct therapeutic approach during tooth movement in more mature patients, leading to a more responsive bone metabolism and favoring more comprehensive orthodontic treatment.

KEYWORDS
orthodontics, photobiomodulation, tooth intrusion

Abbreviations: CBCT, cone beam computed tomography; ELISA, Enzyme-linked immunosorbent assay; J, Joules; LED, light-emitting diode; NFKB, nuclear factor-kappa B; OPG, osteoprotegerin; OPN, osteopontin; PBM, photobiomodulation; RANKL, receptor activator of nuclear factor-kappa B; RANKL, receptor activator of nuclear factor-kappa B ligand.

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INTRODUCTION

The demand for orthodontic treatment among adults has risen significantly, likely due to advancements in dental services and heightened awareness of dentofacial esthetics and functionality among adults.[1] Currently, individuals aged 40–60 years comprise approximately 11.8% of the global population, with projections indicating an increase over the next two decades.[2]

Although age itself does not contraindicate orthodontic treatment, it can present distinct challenges in older individuals. Patients with a history of periodontal disease may display bone defects. While orthodontic treatment can assist in restoring lost periodontal tissue and enhancing long-term stability,[3,4] it is associated with increased risks of marginal bone and attachment loss.[5,6] Additionally, susceptibility to root resorption has been reported to increase with age.[4] Therefore, in older adults, orthodontic treatment is often limited to minor tooth movements and is typically pursued as an adjunct to periodontal therapy for reducing plaque accumulation, correcting gingival and osseous irregularities, improving esthetics, and facilitating prosthetic replacements.[7]

Bone remodeling in adults proceeds at a slower rate than in younger individuals, largely due to reduced osteoblastic activity.[6,8] Normal cells, including osteoblasts, osteoclasts, and osteocytes, undergo a finite number of divisions, which decrease with aging. Consequently, bone deposition diminishes, likely due to a reduced number of osteoblast precursor cells or a shorter osteoblast lifespan. Bone mineral density (BMD) begins to decline in both men and women around age 40, with a marked acceleration in women due to hormonal changes associated with menopause, typically between ages 40 and 50. Hormone deficiencies elevate receptor activator of nuclear factor-kappa B ligand (RANKL) levels, leading to increased recruitment and activation of osteoclasts while reducing their apoptosis.[9] Additionally, studies indicate that RANKL expression and osteoclast numbers in older animals do not return to baseline levels during the postorthodontic retention period. These findings suggest that alveolar bone in younger individuals recovers more rapidly following orthodontic force removal, implying that retention protocols may need adaptation for older patients.[10]

Orthodontic treatment induces localized inflammatory responses through the application of biomechanical forces to teeth, prompting surrounding bone remodeling. Numerous studies have demonstrated that photobiomodulation (PBM) using low-power lasers or light-emitting diodes (LEDs) directly impacts bone formation and resorption by increasing osteoclast numbers on the compression side of the periodontal ligament, thereby stimulating bone resorption. Simultaneously, PBM positively affects bone formation and cell proliferation on the ligament's tension side.[11,12]

PBM has been applied to modulate bone formation, accelerating bone repair following maxillomandibular surgeries and aiding in fracture recovery.[13,14] In orthodontics, PBM has facilitated the regeneration of bone tissue after rapid maxillary expansion.[15,16] In patients with periodontal bone loss, studies evaluating PBM as an adjunctive therapy report significant reductions in inflammation, enhanced repair of periodontal tissues,[17] and improvements in bone density and probing depth.[18]

Despite evidence supporting orthodontic treatment in mature adults,[3,4] there remains a scarcity of studies examining bone remodeling and root resorption risk in this age group. Furthermore, clinical guidelines and supplementary therapeutic approaches for periodontally healthy or compromised older patients are limited. Some recent studies suggest incorporating isoflavones, such as genistein, to enhance the remodeling process by increasing TGF-β1 levels, potentially improving older patients' responses to orthodontic forces.[19]

This study, therefore, aimed to evaluate whether PBM can enhance bone remodeling activity, specifically bone formation, in older adults undergoing orthodontic treatment.

MATERIALS AND METHODS

Sample

This study protocol was reviewed and approved by the Institutional Review Board of Faculdade São Leopoldo Mandic, with all procedures conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from each participant.

A total of 30 molars from 15 patients (mean age 52.7 years; range 40–60 years) were included in a split-mouth design, with 15 teeth in the control group and 15 in the PBM group. Selection criteria included (a) good systemic health, (b) requirement for bilateral intrusion of the upper first molars, (c) presence of adjacent teeth, (d) adequate oral hygiene, and (e) no prior orthodontic treatment. Exclusion criteria encompassed (a) pregnancy or lactation, (b) use of medications potentially affecting orthodontic response (e.g. nonsteroidal anti-inflammatory drugs) and (c) active periodontal disease. Figure 1 presents the study's CONSORT flow diagram.

Patients were selected based on the indication for intrusion of posterior teeth that had extruded due to early loss of opposing teeth, a condition frequently observed in mature adults. The biomechanical setup included anchorage

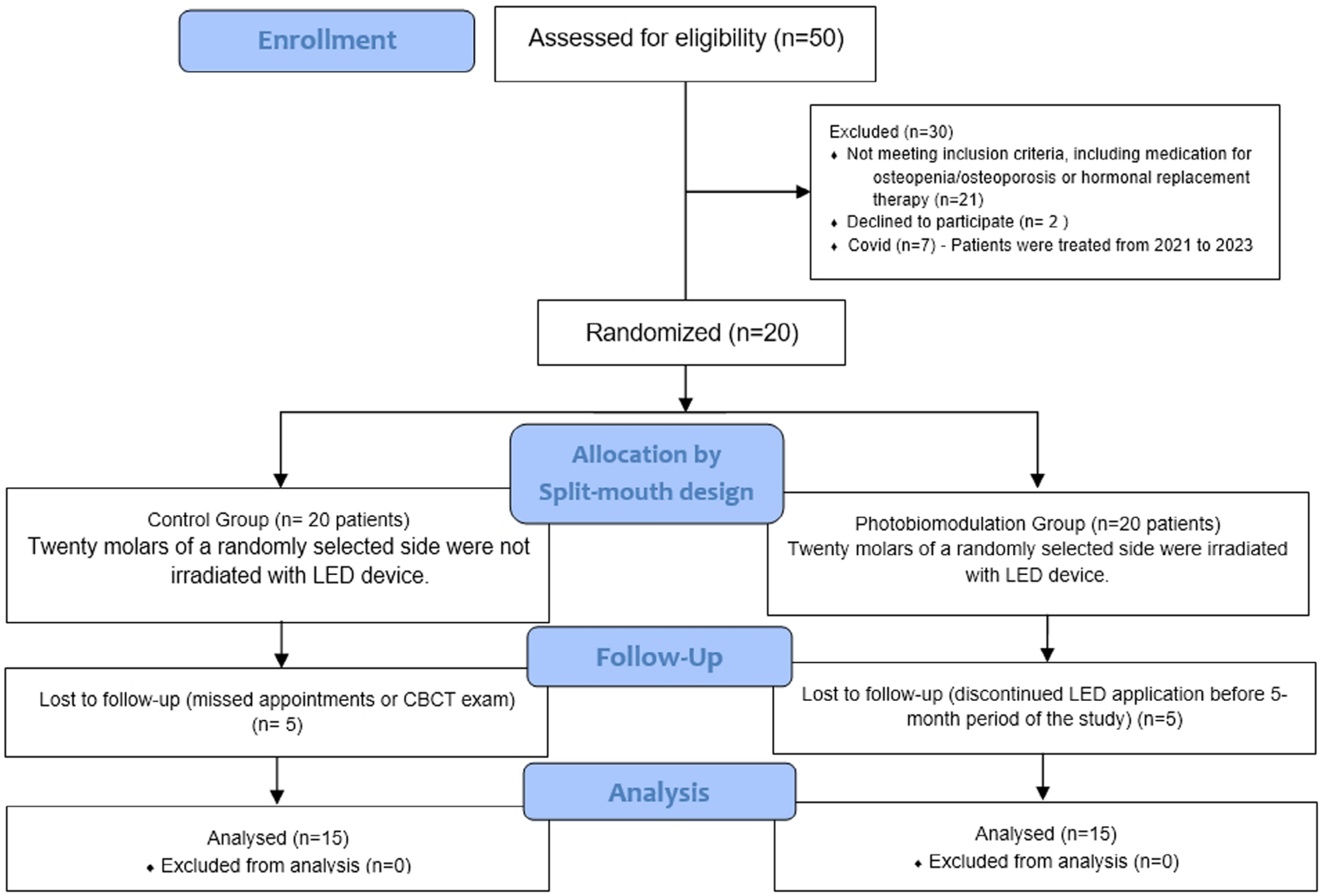

FIGURE 1 CONSORT flow diagram of the study.

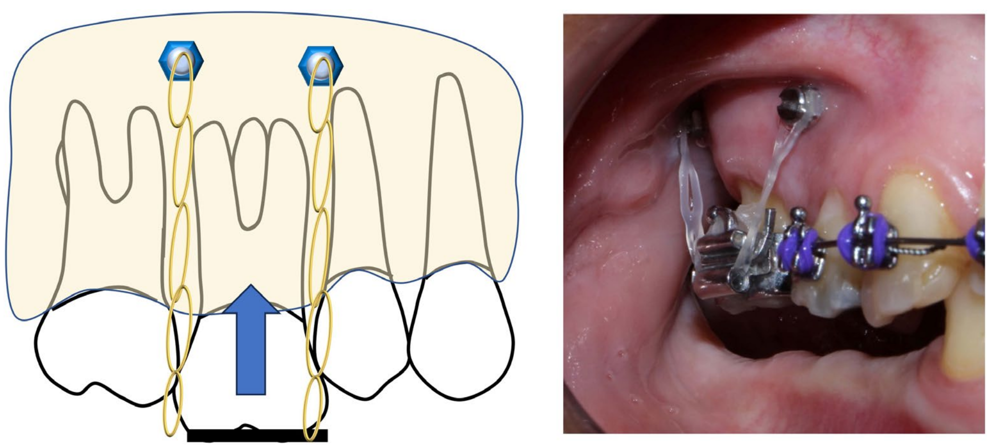

FIGURE 2 Biomechanical devices used in the present study to evaluate tooth movement through upper molar intrusion.

mini-implants, fixed partial appliances, and chain elastics applying 100 g of force (Figure 2).

Photobiomodulation

The PBM device, specifically modified for this study, consisted of a cluster of LEDs (Cosmedical, São Paulo, Brazil) with six infrared LEDs, each emitting at 830 nm with an output power of 5 mW, distributed over a 6 cm^2 area (Figure 2). Patients were instructed in device use and provided with an instruction sheet. The protocol involved positioning the LED cluster over the buccal and palatal sides of the target tooth for 7 min per side, delivering a total dose of 2 J/point.[9] This procedure was repeated every other day for 5 months (Figure 3).[11]

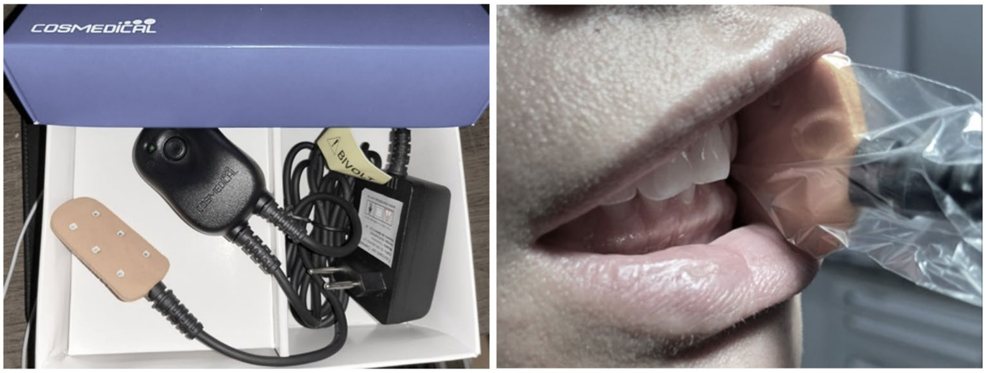

FIGURE 3 Device for photobiomodulation using infrared light-emitting diodes manufactured by Cosmedical (São Paulo, Brazil).

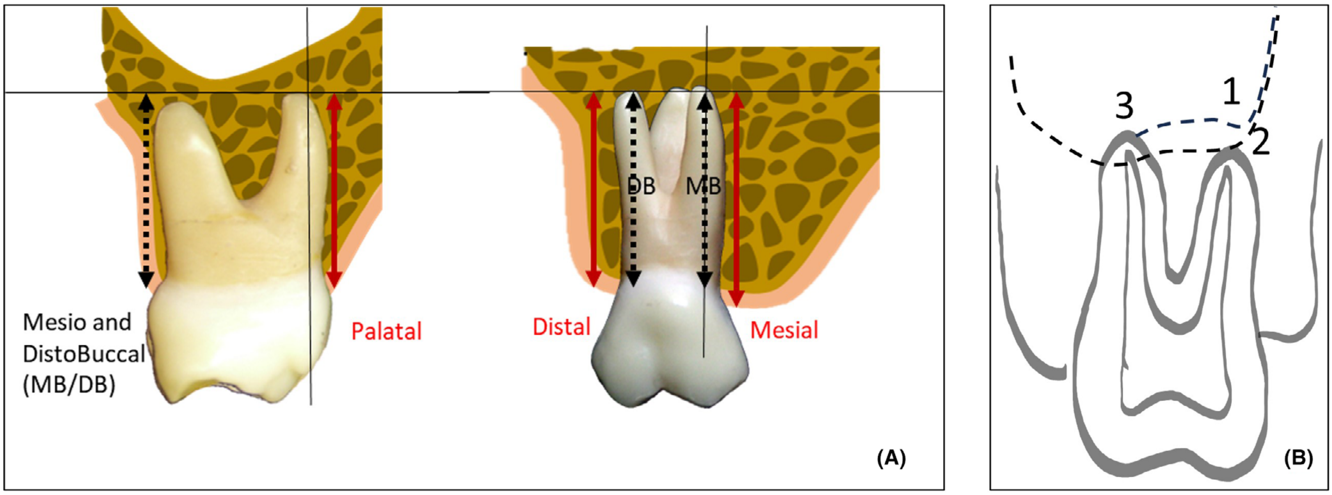

FIGURE 4 (A) Schematic drawings of bone height measurements obtained on the palatal and mesial surfaces of the molars at T0 and T1. (B) Score assigned to the proximity relationship between the root apex and the floor of the maxillary sinus[1]: no contact,[2] in contact, and[3] maxillary sinus floor surrounding the root apex.

Evaluation using cone beam computed tomography (CBCT)

Initial (T0) and final (T1) images were captured for both groups using the i-CAT Next Generation (Imaging Sciences International, Hatfield, PA) with a 13×16 cm field of view, voxel size of 0.25 mm, and exposure settings of 36 mAs and 120 kVp. All data were exported in DICOM format and analyzed with Implastation software (Prodigident, Batavia, IL, USA). Bone height measurements were taken from the alveolar bone crest to the apex of the mesiobuccal, distobuccal, and palatal roots, as well as on the mesial and distal surfaces of the molars. Measurements were made along the long axis of each root (Figure 4), with changes in alveolar bone height calculated by subtracting initial values from final measurements.

Clinical assessment of tooth movement

To assess upper molar intrusion, the distance between the mini-implants and the molar cusp was measured monthly in all patients using a digital caliper (Mitutoyo, São Paulo, Brazil).

Assessment of proximity to the maxillary sinus

The proximity of the intruded molar apex to the maxillary sinus floor was evaluated using a three-point scale[1]: no contact between the apex and the maxillary sinus,[2] root apex in contact with the sinus floor, and[3] maxillary sinus floor surrounding the root apex (Figure 4). For each patient, the root closest to the sinus floor was analyzed.

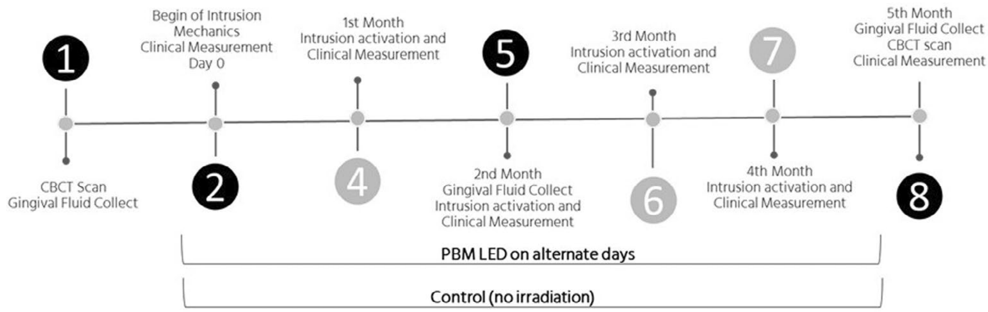

FIGURE 5 Timeline showing the procedures performed in both groups.

Enzyme-linked immunosorbent assay (ELISA)

Mediators in the gingival crevicular fluid (GCF) were quantified using ELISA (eBioscience, San Diego, CA, USA) in accordance with manufacturer instructions. GCF samples were collected using absorbent paper from four sites around the upper molars (buccal, lingual, mesial, and distal surfaces). The concentrations of receptor activator of NFκB (RANK), osteoprotegerin (OPG), and osteopontin (OPN) were measured. Samples were collected on day 0, month 2 (60 days), and month 5 (150 days) of tooth movement and stored at −70°C until analysis.

Frozen samples were reconstituted with 500 μL of RIPA buffer solution (10 mM Tris HCl pH 7.5; 10 mM sodium deoxycholate; 1% Triton X-100; 150 mM NaCl; 0.1% sodium dodecyl sulfate; 2 μg/mL aprotinin, 2 μg/mL pepstatin, and 1 mm phenylmethylsulfonyl fluoride with 1% protease inhibitor). Samples were centrifuged at 10,000g for 15 min at 4°C. For ELISA, 100 μL of detection antibody was added to each well (excluding blank wells), and plates were incubated at 4°C for 16–24 h. Following incubation, plates were washed three times, standards and supernatants were added in duplicate, and plates were washed again after incubation. A 200 μL conjugate was then added and incubated for 60 min at room temperature.

After three additional washes, 200 μL of substrate solution was added, and plates were incubated in the dark for 15 minutes at room temperature. The reaction was halted with 50 μL of stop solution, and absorbance was measured at 450 nm using an automated microplate spectrophotometer (Epoch, Biotek, Winooski, Vermont). Cytokine concentrations were calculated in picograms per milliliter (ng/mL) based on standard curves for each assay. All ELISA assays were blinded and performed in triplicate.

The experimental design and all procedures, measurements, examinations, and sample collections for both PBM and control groups are summarized in Figure 5.

Statistical analysis

The Shapiro–Wilk test was applied to assess the normality of data distributions for each variable. Given the Gaussian distribution and split-mouth study design, paired t-tests were used to analyze tooth movement, OPG, OPN, and RANK expression, as well as bone height measurements at each time point. Statistical analyses were performed using GraphPad Prism 10 software (GraphPad Software, San Diego, CA, USA). A significance level of $p < 0.05$ was applied to all comparisons.

RESULTS

Results showed that molar intrusion was significantly greater in the PBM group at months 2, 3, 4, and 5, with $p < 0.05$ (Figure 6) compared to the control group. Bone height measurements further indicated significantly greater bone heights in the PBM group across all five regions compared to the control group ($p < 0.05$; Figure 7). In contrast, the control group exhibited reductions in bone height (negative values) from T0 to T1 at the mesiobuccal, distobuccal, and palatal aspects of the roots, indicating bone height loss.

For maxillary sinus proximity, 55% of the molars initially showed contact between the root apex and the maxillary sinus floor in both groups. Among these, 100% of intruded molars demonstrated cortical bone of the maxillary sinus bypassing the root apices at the final assessment. In the remaining 35% of molars, there was no initial contact with the sinus floor, though 99% of these molars showed contact with the sinus floor by the final time point, while only 1% maintained their initial condition. The remaining 10% of intruded teeth exhibited initial tracing of the apex by the cortical maxillary sinus floor, with proximity increasing after intrusion. No significant differences in sinus proximity were observed between the PBM and control groups.

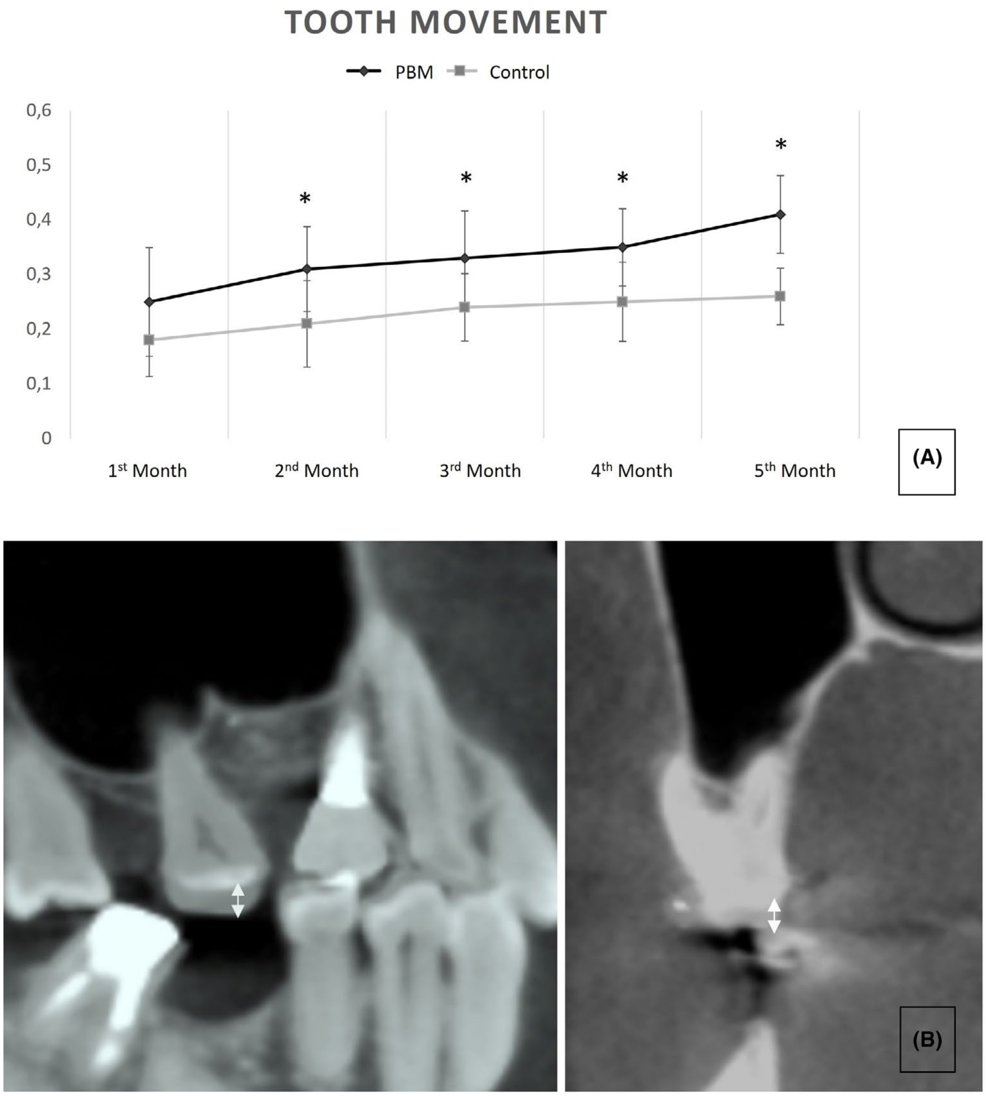

FIGURE 6 (A) Mean and standard deviation of tooth movement values at each month at the PBM and control groups (*–<0.05). (B) Representative image of a superimposition of initial and final intrusion movements (white arrow) of a patient from PBM group. Caption: control, no irradiation; PBM, photobiomodulation.

Analysis of osteoclastic activity, assessed through RANK expression, showed a significant increase in RANK levels in the PBM group at month 3 ($p < 0.05$), followed by a marked reduction at month 5 ($p < 0.05$). This pattern supports PBM-induced bone movement initially and, subsequently, bone repair around the moved tooth over time. OPG expression, associated with the inhibition of osteoclast differentiation,[20] was significantly elevated at month 5 in the PBM group ($p < 0.05$). OPN, a multifunctional glycoprotein involved in bone mineralization and tissue repair,[20] exhibited a significant increase in expression in the PBM group at month 3 relative to the control and an even higher expression by month 5 ($p < 0.05$) (Figure 8).

DISCUSSION

Recent studies suggest that PBM effectively accelerates tooth movement. Cruz et al.,[21] Youssef et al.,[22] and Genc et al.[23] reported increases in movement rates of 20%–40%, with some cases showing a doubling of the rate over 6 months. These studies focused on premolar extraction cases using orthodontic space-closing mechanics in younger patients with healthy periodontal conditions. In the present study, however, the patient selection criteria included extruded molars with indications for intrusion, with most participants being mature adults seeking accelerated orthodontic treatment and prosthetic rehabilitation of the lower arch. The average intrusion rate in the PBM group was 0.31 mm/month, compared to 0.23 mm/month in the nonirradiated group, resulting in a 33% faster movement rate. These results align closely with previous findings on PBM's efficacy in accelerating tooth movement.[21–24]

With an increasing number of adults aged 40–60 years pursuing orthodontic treatment, a deeper understanding of bone remodeling processes, including both resorption and new bone formation, is critical. In this study, the PBM group showed substantial bone height gains across various root surfaces, with increases of 79% at the mesiobuccal root, 81% at the distobuccal root, 75% at the palatal root, 64% on the mesial surface, and 72% on the distal surface. Similarly, other studies have demonstrated that diode lasers exert positive biostimulatory effects on both soft and hard tissues surrounding dental implants, particularly in challenging cases such as narrow mandibular ridges post-ridge-splitting procedure.[25] Another clinical trial assessing PBM's effects on alveolar bone repair in 20 healthy patients following bilateral lower molar extraction reported enhanced trabecular formation, improved connectivity, and increased bone surface area, indicating a positive impact on human socket repair.[26]

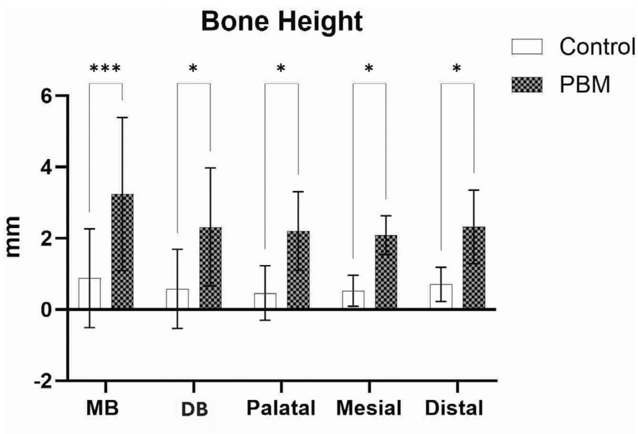

FIGURE 7 Mean and standard deviation values of bone height (T1-T0) on the mesiobuccal (MB), distobuccal (DB), palatal, mesial, and distal sides of both PBM and control groups (*$p < 0.05$, ***$p < 0.001$). Caption: control, no irradiation; PBM, photobiomodulation.

Previous studies have also shown that alveolar bone formation, along with remodeling of the sinus lamina dura, can occur during the distal movement of second premolars toward the maxillary sinus.[27] In the context of molar intrusion, Yao et al.[28] and Kravitz et al.[29] observed that the lamina dura follows the trajectory of molar intrusion, achieving successful bone remodeling. A systematic review by Sun et al.[30] concluded that successful tooth movement toward the maxillary sinus relies on the application of light, continuous forces, biological response through bone deposition, maintenance of an intact sinus membrane, and control over apical root resorption. Although there were differences between groups regarding the initial and final root apex positions relative to the sinus floor, these findings suggest that PBM may stimulate bone repair, potentially mitigating root resorption.[31]

RANK, a key protein in bone remodeling, is present on the surface of osteoclast precursor cells and binds with its ligand RANKL to initiate osteoclast differentiation and activation.[32] In this study, RANK expression significantly increased at month 3 in the PBM group, supporting findings from other studies that PBM can induce bone resorption.[33,34] In orthodontics, elevated RANK and RANKL

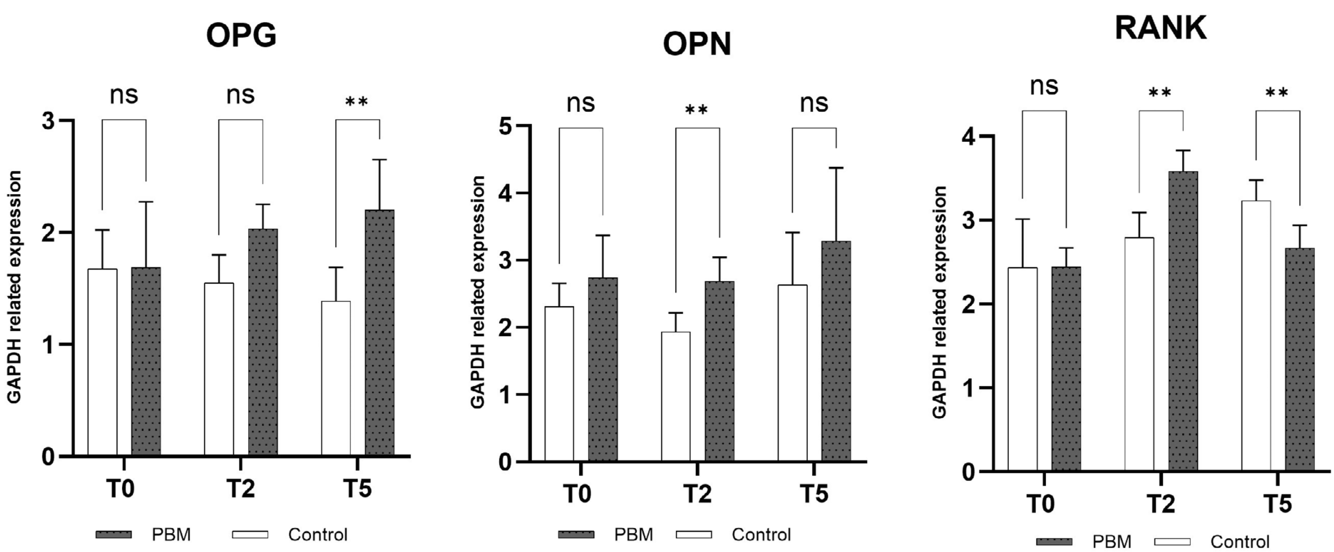

FIGURE 8 Expression of RANK, OPG, and OPN in both control and PBM groups. Caption: control, no irradiation; RANK, receptor activator of NFκB; OPG, osteoprotegerin; OPN, osteopontin; PBM, photobiomodulation; **$p < 0.05$ (statistical test: two-way analysis of variance).

expression induced by PBM has been shown to accelerate tooth movement, thus reducing overall treatment time.[11] Conversely, OPG acts synergistically with RANKL, binding to RANK on osteoclast precursors to inhibit differentiation and activation.[35] While OPG expression showed no differences at month 2, it increased significantly at month 5 in the PBM group, suggesting that PBM ultimately reduces osteoclastogenesis, as indicated by decreased RANK expression at month 5, facilitating the initial stage of bone formation. OPN, a glycoprotein involved in bone matrix regulation, promotes osteoblast activity and supports bone formation and mineralization.[36] The current study observed an increase in OPN expression at months 2 and 5 in the PBM group, suggesting that PBM directly influences bone neoformation in mature adult patients, consistent with findings from prior studies.[37,38] The increased expression of OPN and OPG aligns with tomographic findings, which indicated greater bone height in patients who underwent LED therapy.

Laser sources are characterized by monochromaticity, collimation, and coherence, whereas LEDs may be mono- or polychromatic, emitting diffuse, incoherent light. However, after interacting with biological tissue, laser coherence and collimation typically diminish, rendering the clinical effects of PBM from both sources comparable.[39,40] LEDs offer advantages such as low cost, ease of use, and safe application for patients.

The study's limitations may stem from challenges in accurately measuring bone density, attributed to both the presence of bone loss at the start of the treatment and the resolution limitations of CBCT imaging. Additionally, patients received instructions to use the LED device on the irradiation side on the first day, and compliance was monitored at each consultation, with reinforcement provided to ensure proper LED orientation. No tracking device was used in the study.

These preliminary findings offer valuable insights into the cellular and tissue-level mechanisms underlying PBM in healthy mature adult orthodontic patients. Furthermore, these results may inform clinical recommendations for older patients seeking orthodontic treatment, supporting a comprehensive approach that combines accelerated tooth movement with esthetic and functional outcomes tailored to this demographic.

CONCLUSION

PBM effectively accelerated tooth movement during molar intrusion in mature adult patients and significantly enhanced bone crest height by stimulating bone remodeling, specifically through the increased expression of OPG and OPN. These findings underscore PBM's potential as a valuable adjunctive therapy in orthodontics, particularly for mature patients, by supporting both rapid and stable treatment outcomes.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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