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Original Article

Effects of platelet-rich fibrin combined with low-level erbium laser on soft and hard tissues and bone regeneration around implants

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Abstract: Objective: To evaluate the effects of adjunctive low-energy erbium-doped yttrium aluminum garnet (Er:YAG) laser therapy combined with platelet-rich fibrin (PRF) on peri-implant tissue healing, implant stability, bone regeneration, and postoperative inflammation in dental implant patients. Methods: A retrospective cohort study was conducted with 171 patients who underwent dental implant placement from November 2020 to October 2024. Patients were divided into PRF (PRF alone, n=92) and PRF-ER (PRF combined with low-energy Er:YAG laser therapy, n=79). Clinical parameters, including modified plaque index (mPI), modified sulcus bleeding index (mSBI), probing depth (PD), and implant stability quotient (ISQ) by resonance frequency analysis, were assessed at 2 weeks, 6 weeks, and 3 months post-implantation. Peri-implant crevicular fluid was collected for osteoprotegerin (OPG) quantification. Radiographic assessments of bone density (BD) and ridge measurements were performed using cone-beam computed tomography at baseline and 3 months. Postoperative inflammation and healing were evaluated by visual inspection and the Landry Index. Results: At 3 months postoperatively, the PRF-ER group showed significantly lower mPI, mSBI, and PD, and higher ISQ compared to the PRF group (all $P<0.05$). OPG levels were significantly higher in the PRF-ER group at 3 months, as were BD, horizontal ridge, and vertical ridge measurements (all $P<0.05$). Soft tissue thickness remained similar. A greater proportion of PRF-ER patients showed no inflammation and optimal healing. Conclusion: Adjunctive low-energy Er:YAG laser therapy with PRF significantly improves peri-implant tissue healing, implant stability, bone regeneration, and reduces postoperative inflammation compared to PRF alone in dental implant patients. These findings support the clinical utility of combined modality therapy for enhancing peri-implant outcomes.

Keywords: Platelet-rich fibrin, Er:YAG laser, dental implants, bone regeneration, implant stability

Introduction

Dental implant therapy has revolutionized the rehabilitation of partially and completely edentulous patients, offering a predictable means of restoring masticatory function, phonetics, and esthetics [1]. Titanium implants have shown survival rates exceeding 90% over long-term follow-up [2]. However, early peri-implant tissue complications, such as marginal bone loss, delayed wound healing, and peri-implant mucositis, remain clinically relevant and can compromise implant prognosis [3]. Maintaining a controlled inflammatory response and promoting tissue repair in the postoperative period are crucial; disturbances in these processes, due to microbial challenge, host factors, or surgical trauma, can impede soft-tissue sealing and bone apposition [4]. Consequently, adjunctive therapies that modulate inflammation, enhance angiogenesis, and accelerate osteogenesis have garnered significant research interest [4].

Autologous platelet concentrates, particularly PRF, have emerged as a biological strategy to enhance both hard and soft tissue healing in

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oral surgeries [5]. PRF is obtained through single-spin centrifugation without anticoagulants, yielding a three-dimensional fibrin matrix enriched with platelets, leukocytes, and growth factors like platelet-derived growth factor (PDGF), transforming growth factor-β (TGF-β), and vascular endothelial growth factor (VEGF) [6]. Unlike platelet-rich plasma, PRF's slow polymerization releases bioactive molecules over 7 to 14 days, promoting chemotaxis, cellular proliferation, and angiogenesis [7]. Clinical applications of PRF in ridge preservation, sinus augmentation, and soft tissue grafting have shown improvements in wound stability, bone fill, and mucosal healing, though outcomes vary based on preparation protocols and patient factors [8].

Similarly, low-level laser therapy (LLLT) - also called photobiomodulation - has been used in dental tissues to stimulate cellular metabolism, reduce inflammation, and promote tissue regeneration [9]. Lasers operating in the low-power range (0.5-2.0 J per application) and wavelengths from 600 to 1,064 nm enhance mitochondrial activity through cytochrome c oxidase absorption, leading to increased adenosine triphosphate (ATP) synthesis and osteoblastic and fibroblastic differentiation [10]. Er:YAG lasers (2,940 nm) induce micro-explosive cavitation in water-rich tissues at subablative settings, promoting mechanotransduction and extracellular matrix synthesis without thermal damage [11]. Studies show that LLLT can accelerate bone healing, enhance osteogenic markers, and reduce postoperative pain and edema [12]. However, clinical translation has been inconsistent due to variations in laser parameters and treatment timing [13].

Given the complementary mechanisms of PRF and LLLT - one providing a biologic scaffold enriched with autologous growth factors and the other enhancing cellular function through photonic stimuli - it is plausible that their combination may have synergistic effects on peri-implant tissue regeneration [12, 14]. Preliminary animal models suggest that lasers can modulate growth factor release from platelet concentrates by altering fibrin network permeability, while LLLT upregulates growth factor receptor expression on osteoblasts and endothelial cells, enhancing responsiveness to PRF-derived signals [15]. Both therapies possess anti-inflammatory and antimicrobial properties that may reduce early bacterial colonization and excessive cytokine release, thus preserving the regenerative microenvironment [15].

Despite promising preclinical data, few clinical trials have rigorously evaluated the combined use of PRF and low-level Er:YAG laser therapy around dental implants [16]. Existing studies are limited by small sample sizes, short follow-up periods, and inconsistent outcome measures [17]. Comprehensive assessments of soft tissue parameters (plaque index, sulcus bleeding index, probing depth), implant stability quotient (ISQ), and three-dimensional bone regeneration (bone density [BD], ridge width, and height via cone-beam computed tomography) are sparse. Furthermore, the biological mechanisms underlying these therapies, such as modulation of the receptor activator of nuclear factor κB ligand/osteoprotegerin (RANKL/OPG) axis and laser-induced mechanotransductive signaling, require clinical validation. This retrospective cohort study aims to compare the effects of PRF alone versus PRF combined with low-level Er:YAG laser therapy on peri-implant soft and hard tissue healing, implant stability, and postoperative inflammation.

Materials and methods

Inclusion and exclusion criteria

Inclusion criteria: Patients eligible for inclusion in this study met the following conditions: (1) aged 18 to 70 years, having undergone dental implant surgery at least three months prior; (2) exhibited healthy periodontal tissues, with adjacent implants in cases of multiple implants; (3) maintained overall good systemic health, classified as ASA I or II by the American Society of Anesthesiologists [18], and stable occlusion; (4) demonstrated adequate oral care before and after surgery; (5) had complete medical records containing all necessary information for the study.

Exclusion criteria: Patients were excluded based on the following criteria: (1) heavy smoking habits (more than 20 cigarettes per day, and/or pipe or cigar smoking); (2) thin gingival biotype with less than 4mm of keratinized gingiva around teeth; (3) history of immunosuppressive therapy or treatment with steroids or other medications affecting bone metabolism

(e.g., bisphosphonates); (4) previous radiation therapy to the head and neck region; (5) acute or chronic oral infections post-surgery (including ongoing periodontal infections); (6) extensive bone augmentation during implant surgery (involving large autogenous bone grafts from intraoral or extraoral donor sites).

A retrospective analysis was conducted involving 171 patients who underwent dental implant surgery at Xi'an Jiao Tong University Stomatologic Hospital & College from November 2020 to October 2024. Based on the treatment received, patients were divided into two groups: the PRF group (n=92), which received only PRF treatment, and the PRF-ER group (n=79), which received both PRF and low-energy erbium laser therapy.

Patient data were collected from the medical record system, including demographic information, implant characteristics, clinical parameters (such as plaque index, gingival sulcus bleeding index, probing depth (PD), and ISQ), OPG levels, radiographic parameters (BD, horizontal ridge measurements (HRM), vertical ridge level [VRL], and soft tissue thickness [STT]), and postoperative inflammation assessment.

The study was approved by the Institutional Review Board and Ethics Committee of Xi'an Jiao Tong University Stomatologic Hospital & College. Since the study involved only de-identified patient data with no potential risk to the patients, informed consent was waived, in accordance with the regulatory and ethical standards for retrospective studies.

Treatment procedure

PRF Group: Patients in this group received PRF treatment. Prior to implantation, 2×10 ml of venous blood was collected from the antecubital area and centrifuged in glass-coated plastic tubes. Using the IntraSpin machine (IntraSpin, Intra-Lock International Inc, USA), the tubes were centrifuged at 2,700 RPM for 12 minutes, resulting in three layers: a top creamy plasma layer, a red bottom layer containing red blood cells, and a middle layer with the fibrin clot. The top layer was removed, and the middle layer was collected using sterile forceps, then transferred to the PRF box with the Xpression tray of the IntraSpin system. After five minutes, the membrane was ready for use at the surgical site.

Before implantation, the PRF membrane was wrapped around the dental implant. The implants used (Multysystem, Lissone, Italy) were root-form threaded implants with an internal hexagon design, made from pure titanium, with lengths ranging from 11-13 mm and diameters from 3.5-5 mm. The implant system used was the Astra Tech Dental Implant System® by Dentsply Sirona, Sweden. Postoperative medication included routine antibiotics (Amoxicillin 750 mg every 8 hours for 7 days), analgesics (Ibuprofen 600 mg every 8 hours for 4 days), and mouthwash (0.12% chlorhexidine digluconate, rinsing for 30-60 seconds three times daily for 2-3 weeks).

PRF-ER group: In addition to PRF treatment, patients in the PRF-ER group received low-energy erbium laser therapy. After the implantation procedure, an Er:YAG laser with a wavelength of 2,940 nm (Fotona Lightwalker Dental Laser System, Fotona, Slovenia) was applied to the implant site in a mesiodistal direction for 60 seconds using the R-24 handpiece. The pulse repetition frequency was set at 30 Hz. Each treatment session utilized the laser at a maximum energy of 2 J, with an energy density of 7.07 J/cm^2 per implant. The total energy density applied to each implant at the end of the treatment was 28 J/cm^2. Patients in the PRF-ER group received laser irradiation immediately after implant placement, and again at 2 weeks, 6 weeks, and 3 months post-implantation.

Evaluation of clinical parameters

Postoperative follow-up was conducted at 2 weeks, 6 weeks, and 3 months after implant placement using a UNC-15 periodontal probe (PCPUNC15, Hu-Friedy, USA) across all four surfaces of the implant (buccal, lingual, mesial, and distal). Clinical parameters recorded during each visit included the Modified Plaque Index (mPI), Modified Sulcus Bleeding Index (mSBI), and PD. These parameters were used as important prognostic indicators for assessing the long-term success and stability of the implants.

mPI: The mPI [19] was used to evaluate the condition of hard (e.g., teeth and adjacent calculus) and soft tissues (such as gingiva) around

the implant. The index is scored on a scale from 0 to 3: 0 indicates no detectable plaque; 1 indicates plaque is noticeable only when a probe runs over the smooth surface of the implant; 2 indicates visually detectable plaque; and 3 indicates an abundance of soft deposits.

mSBI: The mSBI [20] was used to assess the degree of inflammation in the soft and hard tissues around the implant. The scoring scale ranges from 0 to 3: 0 indicates no bleeding on probing; 1 indicates isolated bleeding spots; 2 indicates blood forming a confluent red line along the margin; and 3 indicates severe or profuse bleeding.

PD: PD [21] was used to assess the presence and extent of hard tissue damage. A normal PD ranges from 1 to 3 millimeters, with a greater PD indicating poorer periodontal health.

Resonance frequency analysis (RFA): To evaluate the integration of the implant with surrounding bone tissue, RFA was performed using the Osstell™ Mentor device (Integration Diagnostics, Osstell, Sweden). A standardized, fixed-length device (Smartpeg™ Integration Diagnostics) was inserted and manually screwed into each implant. Sensor detection was conducted with the Osstell™ Mentor Probe, pointing the tip towards the small magnet at the top of the Smartpeg™ at a distance of 2-3 mm. The device emits a beep and displays an ISQ [22]. Measurements were taken on the buccal, lingual, mesial, and distal surfaces of the implant to obtain a global average. A higher frequency (kHz) indicates a more rigid implant/bone system. The ISQ scale ranges from 1 to 100, with higher numbers indicating greater implant stability.

Evaluation of OPG levels

To assess bone regeneration, peri-implant crevicular fluid (PICF) samples were collected from patients at baseline, 2 weeks, 6 weeks, and 3 months after implant placement. After isolating the implant site, paper points were used to collect the samples, and the soft tissue was gently dried with an air syringe. The paper point was carefully inserted into the gingival sulcus until slight resistance was felt and left in place for 30 seconds. Contaminated paper points were excluded. The collected paper points were stored in Eppendorf vials at -80°C until analysis. OPG [23] levels in PICF were determined using a human OPG Instant ELISA Kit (BMS2021INST, Bender MedSystems GmbH, Vienna, Austria), as provided by Bioscience.

Evaluation of radiographic parameters

Cone-beam computed tomography (CBCT) scans were performed using a Planmeca machine (ProMax 3D Mid, Planmeca, Finland) at baseline and 3 months post-implantation. The scans had a tube voltage of 90 kV and a tube current of 12 mA, adjusted according to the field of view for pulsed exposure. CBCT data included BD, HRM, VRL, STT, and crestal gingival thickness (CGT). BD values were used to assess bone regeneration, HRM and VRL to evaluate hard tissue (gingiva) recession, ST to assess soft tissue thickness, and CGT to define the distance between the gingiva surface and underlying bone, measured 1 mm from the alveolar crest.

BD values [24], expressed in grayscale, were obtained using BlueSkyPlan software (BlueSkyPlan, BlueSkyBio, USA). The software automatically displayed grayscale differences by moving the cursor across regions. BD was measured at fixed points in the software at baseline and 3 months post-implantation. It was categorized into two planes: coronal and sagittal. Two lines parallel to the implant length were drawn for each plane and divided into cervical, middle, and apical thirds. These lines were recorded away from the implant to avoid titanium artifacts. BD values were recorded in Hounsfield Units (HU).

Evaluation of postoperative inflammation

Postoperative inflammation was assessed 7 days after surgery. A subjective binary visual inspection (yes/no) was conducted, followed by an evaluation of soft tissue healing using the Landry Index (LI) [2]. Healing was estimated using a 5-grade scoring index based on four parameters: tissue color, palpation response, granulation tissue, and incision margin. A modified index for post-extraction sites, using a binary score (0/1) out of a total of 7, was applied, evaluating redness, granulation tissue, suppuration, swelling, epithelialization (partial/complete), bleeding, and pain upon palpation.

Table 1. Comparison of demographic characteristics between the two groups

Parameters	PRF group (n=92)	PRF-ER group (n=79)	t/χ^2	P
Age (years)	55.62 ± 8.45	55.61 ± 9.93	0.004	0.997
BMI (kg/m^2)	23.45 ± 2.13	23.52 ± 2.06	0.209	0.835
Male/Female [n (%)]	50 (54.35%)/42 (45.65%)	45 (56.96%)/34 (43.04%)	0.118	0.732
Smoking [n (%)]			1.617	0.204
Yes	32 (34.78%)	35 (44.30%)		
No	60 (65.22%)	44 (55.70%)		
Drinking [n (%)]			0.081	0.776
Yes	61 (66.30%)	54 (68.35%)		
No	31 (33.70%)	25 (31.65%)		
Diabetes [n (%)]			1.859	0.173
Yes	16 (17.39%)	8 (10.13%)		
No	76 (82.61%)	71 (89.87%)		
Regular medication intake [n (%)]			0.002	0.969
Yes	79 (85.87%)	68 (86.08%)		
No	13 (14.13%)	11 (13.92%)		
ASA classification [n (%)]			1.272	0.259
Type I	44 (47.83%)	31 (39.24%)		
Type II	48 (52.17%)	48 (60.76%)		

BMI: Body Mass Index; PRF: Platelet-Rich Fibrin; PRF-ER: Platelet-Rich Fibrin Combined with Low-Level Erbium Laser.

Statistical analysis

Data analysis was performed using SPSS statistical software (version 29.0; SPSS Inc., Chicago, IL, USA). Categorical data were reported as [n (%)]. A chi-square test (χ^2) was applied based on basic calculation formulas. The Shapiro-Wilk test assessed the normality of continuous variables; if normality was met, measurement data were presented as mean ± standard deviation (x ± sd) and compared between groups using an independent samples t-test. A *P*-value of less than 0.05 was considered statistically significant.

Results

Comparison of basic data

The demographic and implant characteristics of the two groups were comparable, with no statistically significant differences observed (all P>0.05) (**Tables 1**, **2**). These findings suggest that the baseline characteristics of the study participants were well matched, minimizing potential confounding effects in subsequent analyses of clinical outcomes.

Comparison of clinical parameters

At 2 weeks post-implantation, no significant differences were observed between the PRF and PRF-ER groups in the mPI, mSBI, or ISQ (all P>0.05). However, the PRF-ER group exhibited a significantly higher ISQ and greater PD (**Figures 1**-**4**). By 6 weeks, the PRF-ER group showed significantly lower mPI and PD, and higher ISQ (P<0.05), while mSBI was lower in the PRF-ER group, though not reaching statistical significance (P>0.05). At 3 months, the PRF-ER group maintained significantly better outcomes, with lower mPI, mSBI, and PD, and higher ISQ compared to the PRF group (all P<0.05).

Comparison of OPG levels

No significant differences in peri-implant OPG levels were observed between the PRF and PRF-ER groups at baseline, 2 weeks, or 6 weeks post-implantation (all P>0.05). However, at 3 months, the PRF-ER group exhibited significantly higher OPG concentrations compared to the PRF group (P<0.001) (**Table 3**).

Table 2. Comparison of implant characteristics between the two groups

Parameters	PRF group (n=92)	PRF-ER group (n=79)	χ^2	P
Number of implants placed [n (%)]			0.377	0.539
Single units	21 (22.83%)	15 (18.99%)		
Multiple units	71 (77.17%)	64 (81.01%)		
Implants position [n (%)]			0.482	0.786
Maxilla	36 (39.13%)	27 (34.18%)		
Mandible	46 (50.00%)	42 (54.43%)		
Both	10 (10.87%)	10 (12.66%)		
Implants diameter (mm) [n (%)]			1.334	0.248
3.5-4.2	43 (46.74%)	30 (37.97%)		
4.3-5	49 (53.26%)	49 (62.03%)		
Implants length (mm) [n (%)]			1.116	0.572
11	46 (50.00%)	38 (48.10%)		
12	41 (44.57%)	39 (49.37%)		
13	5 (5.43%)	2 (2.53%)		

PRF: Platelet-Rich Fibrin; PRF-ER: Platelet-Rich Fibrin Combined with Low-Level Erbium Laser.

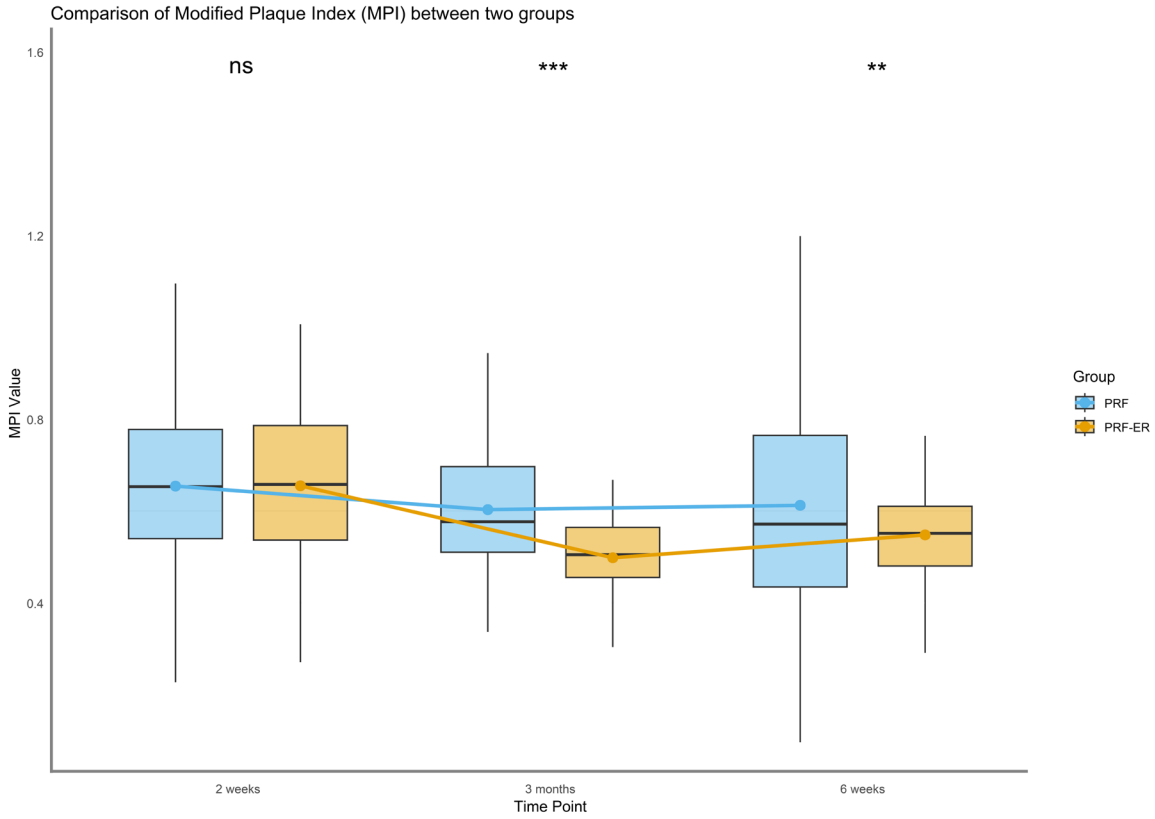

Figure 1. Comparison of modified plaque index between the two groups. ns represents no significant differences, ** represents P<0.01, *** represents P<0.001. PRF: Platelet-Rich Fibrin; PRF-ER: Platelet-Rich Fibrin Combined with Low-Level Erbium Laser.

Comparison of radiographic parameters

At baseline, no statistically significant differences were observed in radiographic parameters, including BD, HRM, VRL, ST, or CGT, between the PRF and PRF-ER groups (all P>0.05) (**Table 4**). However, at 3 months postoperatively, the PRF-ER group demonstrated

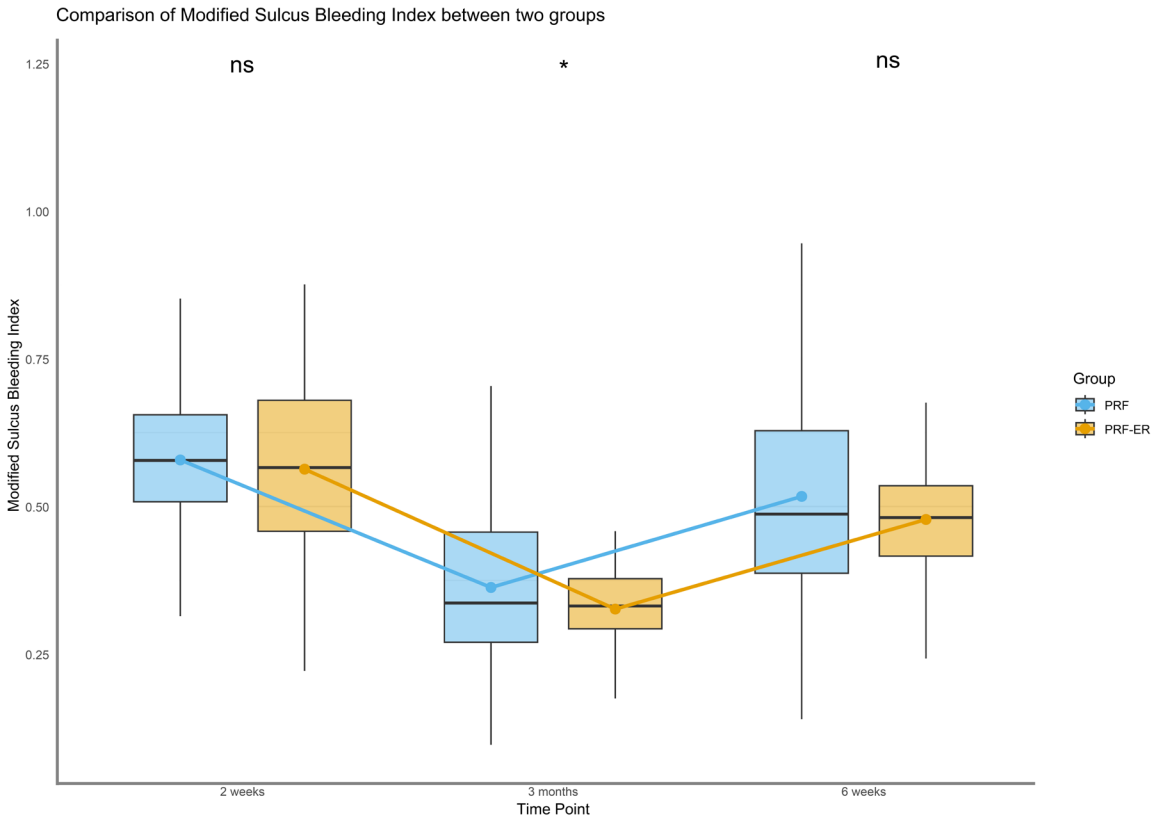

Figure 2. Comparison of modified sulcus bleeding index between the two groups. ns represents no significant differences, * represents P<0.05. PRF: Platelet-Rich Fibrin; PRF-ER: Platelet-Rich Fibrin Combined with Low-Level Erbium Laser.

significantly greater BD, higher HRM, and increased VRL compared to the PRF group (all P<0.05) (**Table 5**). ST and CGT remained similar between the groups at 3 months (all P>0.05). **Figure 5** shows the pre- and post-treatment sagittal CBCT views for both groups. Three months post-treatment, the PRF group showed increased bone volume and ridge height compared to baseline (both P>0.05). The PRF-ER group demonstrated even more pronounced improvements in these parameters (both P>0.05).

Comparison of postoperative inflammation

At 3 months postoperatively, visual examination revealed a significantly higher proportion of patients without inflammation in the PRF-ER group compared to the PRF group (P=0.011) (**Table 6**). Furthermore, assessment of the healing index showed that a greater percentage of PRF-ER patients achieved the highest healing score compared to the PRF group (P=0.019).

Discussion

Dental implant therapy has revolutionized restorative dentistry by offering a reliable solution for replacing missing teeth and restoring masticatory function [17]. Since the pioneering work on osseointegration by Brånemark in the 1970s, implant success rates have steadily improved. However, early failures and peri-implant tissue complications remain clinically significant [25]. The initial healing phase following implant placement is critical: a controlled inflammatory response must transition smoothly into the proliferative and remodeling phases to ensure stable bone-implant contact and a robust peri-implant mucosal seal [26]. Any imbalance - whether due to excessive inflammation, bacterial contamination, or inadequate angiogenesis - can compromise both hard and soft tissue outcomes [27]. Therefore, adjunctive therapies that can modulate inflammation, enhance neovascularization, and accelerate tissue regeneration have gained considerable research interest.

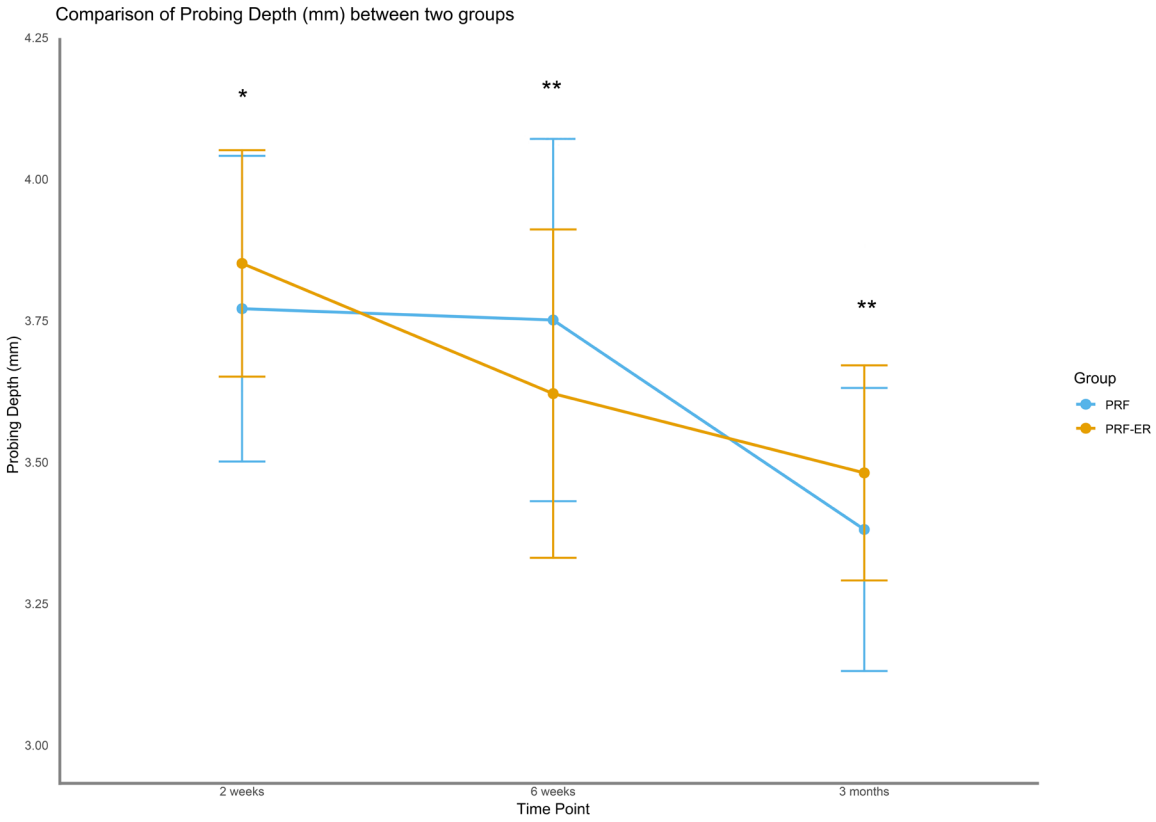

Figure 3. Comparison of probing depth (mm) between the two groups. * represents P<0.05, ** represents P<0.01. PRF: Platelet-Rich Fibrin; PRF-ER: Platelet-Rich Fibrin Combined with Low-Level Erbium Laser.

PRF was introduced as a second-generation platelet concentrate, prepared in a single centrifugation step without anticoagulants [28]. Unlike platelet-rich plasma PRF forms a three-dimensional fibrin network capable of sustaining the release of growth factors over 7-14 days [29]. This autologous fibrin matrix entraps platelets, leukocytes, and cytokines, including PDGF, TGF-β, VEGF, IGF, and EGF, which play crucial roles in chemotaxis, cell proliferation, angiogenesis, and extracellular matrix synthesis [30]. Clinically, PRF has been applied in various oral surgical procedures - such as sinus lifts, ridge preservation, and soft tissue augmentation - with generally favorable outcomes in terms of wound healing and bone regeneration [30, 31]. Its ease of preparation, low cost, and lack of exogenous additives make PRF an attractive biomaterial for chairside use [32].

Simultaneously, LLLT, also known as photobiomodulation, has emerged as a non-invasive modality to stimulate cellular metabolism and modulate inflammatory responses [33]. Early applications of lasers in dentistry focused on hard tissue ablation and soft tissue surgery, but subsequent research showed that sub-ablative laser energy at specific wavelengths enhances mitochondrial activity, increases ATP production, and triggers secondary messenger cascades involving reactive oxygen species and nitric oxide [34]. These photochemical and photophysical interactions underlie LLLT's reported benefits: accelerated wound closure, reduced postoperative pain and edema, and enhanced osteoblastic differentiation [35]. However, parameter standardization - wavelength, energy density, and pulse duration - remains a challenge, and clinical benefits can vary across protocols.

The rationale for combining PRF with low-level erbium laser irradiation lies in their complementary mechanisms of action [36]. PRF provides a biological scaffold rich in growth factors and immune cells, while LLLT delivers an external stimulus that amplifies cellular activities within and around the scaffold [37]. In vitro

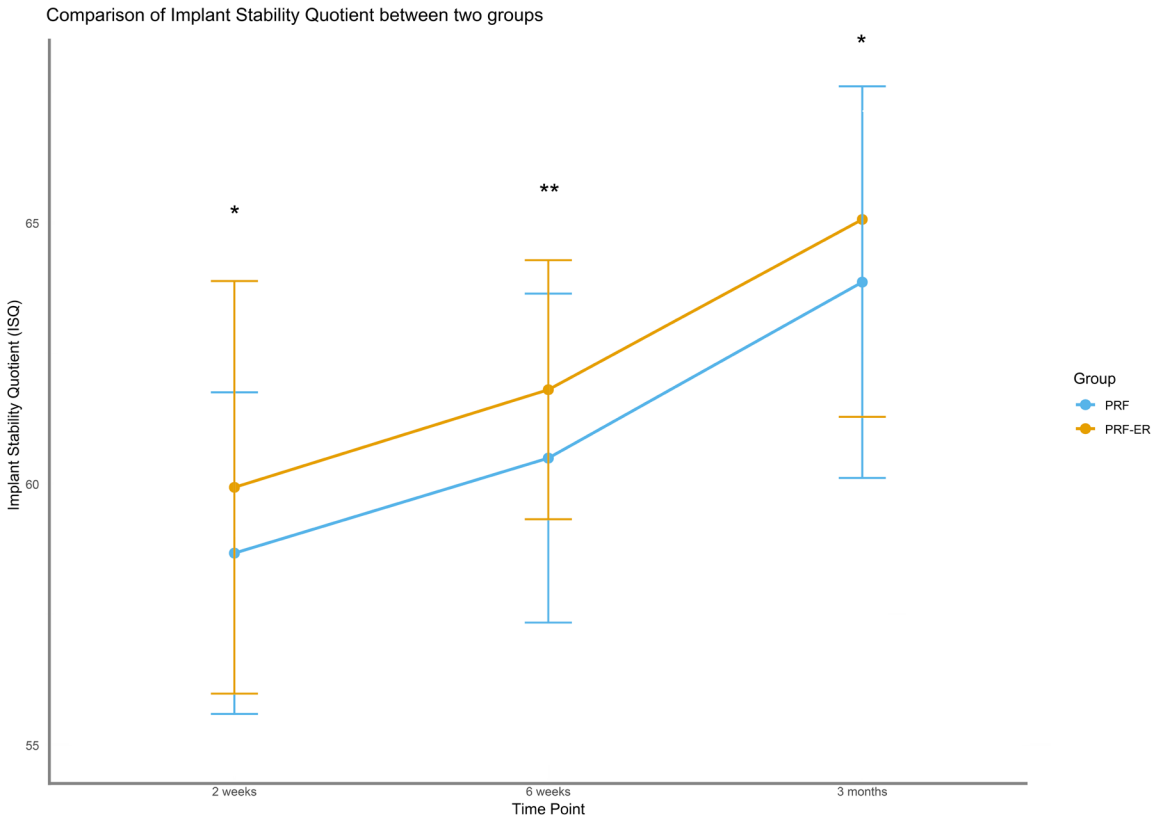

Figure 4. Comparison of implant stability quotient between the two groups. * represents P<0.05, ** represents P<0.01. PRF: Platelet-Rich Fibrin; PRF-ER: Platelet-Rich Fibrin Combined with Low-Level Erbium Laser.

Table 3. Comparison of osteoprotegerin level (pg/ml) between the two groups

Parameters	PRF group (n=92)	PRF-ER group (n=79)	t	P
Baseline	639.51 ± 249.08	656.33 ± 125.36	0.569	0.570
2 weeks	696.23 ± 249.79	729.08 ± 107.78	1.143	0.255
6 weeks	758.56 ± 259.84	783.75 ± 101.55	0.857	0.393
3 months	415.37 ± 78.39	784.25 ± 108.31	25.141	<0.001

PRF: Platelet-Rich Fibrin; PRF-ER: Platelet-Rich Fibrin Combined with Low-Level Erbium Laser.

Table 4. Comparison of the radiographic parameters between the two groups (baseline)

Parameters	PRF group (n=92)	PRF-ER group (n=79)	t	P
BD	826.52 ± 44.47	835.43 ± 28.68	1.578	0.117
HRM	8.36 ± 1.23	8.42± 1.45	0.281	0.779
VRL	2.58 ± 0.77	2.66 ± 0.83	0.660	0.510
STT	1.59 ± 0.32	1.56 ± 0.59	0.419	0.676
CGT	0.84 ± 0.25	0.79 ± 0.26	1.187	0.237

BD: Bone density; HRM: Horizontal ridge measurement; VRL: Vertical ridge level in reference to CEJ; STT: Soft tissue thickness; CGT: Crestal gingival thickness; PRF: Platelet-Rich Fibrin; PRF-ER: Platelet-Rich Fibrin Combined with Low-Level Erbium Laser.

studies suggest that laser irradiation can enhance growth factor release from platelet concentrates by increasing fibrin permeability and promoting microstructural rearrangements [37, 38]. Photobiomodulation may also up-regulate receptor expression on target cells - osteo-

Table 5. Comparison of the radiographic parameters between the two groups (3 months postop)

Parameters	PRF group (n=92)	PRF-ER group (n=79)	t	P
BD	898.25 ± 22.64	960.03 ± 25.71	16.709	<0.001
HRM	7.38 ± 0.76	7.66 ± 0.92	2.170	0.031
VRL	3.55 ± 0.24	3.71 ± 0.52	2.650	0.009
STT	1.76 ± 0.39	1.73 ± 0.34	0.557	0.578
CGT	0.85 ± 0.24	0.81 ± 0.21	1.168	0.245

BD: Bone density; HRM: Horizontal ridge measurement; VRL: Vertical ridge level in reference to CEJ; STT: Soft tissue thickness; CGT: Crestal gingival thickness; PRF: Platelet-Rich Fibrin; PRF-ER: Platelet-Rich Fibrin Combined with Low-Level Erbium Laser.

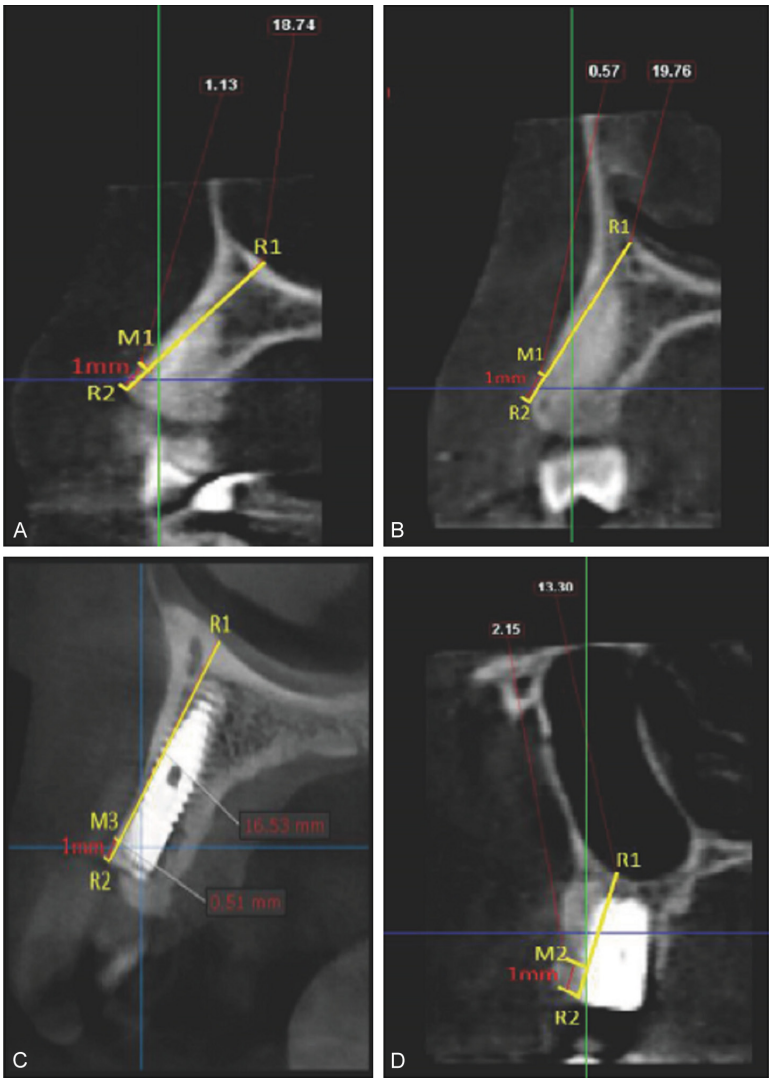

Figure 5. Sagittal CBCT views of pre- and post-treatment in the PRF and PRF-ER groups. A. Pre-treatment CBCT (PRF group). B. Pre-treatment CBCT (PRF-ER group). C. Post-treatment CBCT (PRF group). D. Post-treatment CBCT (PRF-ER group).

blasts, fibroblasts, and endothelial cells - making them more responsive to PRF-derived signals [39]. Moreover, the anti-inflammatory effects of LLLT can reduce excessive cytokine release during the early healing phase, preserving the integrity of the PRF scaffold and reducing catabolic processes that could impair regenerative outcomes [40].

Mechanistically, PRF's sustained delivery of PDGF and TGF-β recruits mesenchymal stem cells to the implant site, promoting their proliferation and osteogenic differentiation [40]. VEGF within PRF stimulates angiogenesis, ensuring adequate blood supply for newly forming tissues [41]. When erbium laser energy at 2,940 nm is applied in a low-power, pulsed mode, absorption by water molecules generates micro-explosive cavitation effects, providing mechanical stimuli to adjacent cells [41]. These micro-stresses activate mechanotransduction pathways - such as focal adhesion kinase and integrin signaling - resulting in increased cytoskeletal organization and enhanced extracellular matrix deposition [37]. Simultaneously, photonic energy absorbed by cytochrome c oxidase in mitochondria accelerates ATP synthesis and modulates gene expression profiles, up-regulating osteogenic markers such as Runx2, alkaline phosphatase, and osteocalcin [41].

Table 6. Comparison of postoperative inflammation between the two groups

Parameters	PRF group (n=92)	PRF-ER group (n=79)	χ^2	P
Visual examination [n (%)]			6.435	0.011
Without inflammation	38 (41.30%)	48 (60.76%)		
With inflammation	54 (58.70%)	31 (39.24%)		
HI [n (%)]			5.510	0.019
1-4	66 (71.74%)	43 (54.43%)		
5	26 (28.26%)	36 (45.57%)		

PRF: Platelet-Rich Fibrin; PRF-ER: Platelet-Rich Fibrin Combined with Low-Level Erbium Laser; HI: healing index.

The observed up-regulation of OPG in peri-implant crevicular fluid following combined therapy suggests a shift in the RANKL/OPG balance toward bone preservation. These findings are consistent with those of Tsuka et al. [42], who demonstrated that Er:YAG laser irradiation at 2.0 W significantly increased the expression levels of bone metabolism-related factors, including ALP, BSP, and OPG, in osteoblast-like Saos 2 cells. Their in vitro study showed that Er:YAG laser irradiation enhanced OPG gene and protein expression, suggesting a mechanism for promoting bone formation and reducing bone resorption. This consistency further supports the role of Er:YAG laser in enhancing bone regeneration. OPG, a decoy receptor for RANKL, inhibits osteoclast differentiation and activity, thereby reducing bone resorption. It is plausible that the synergy between PRF's TGF-β content and laser-induced activation of Wnt/β-catenin signaling amplifies OPG transcription in osteoblast precursors [33, 34]. This mechanism not only promotes net bone formation but also stabilizes crestal bone levels during the critical early remodeling phase, when marginal bone loss is most likely to occur.

Soft tissue healing around implants is critical for long-term success, as a robust mucosal seal prevents bacterial ingress and peri-implant inflammation. The fibrin matrix of PRF acts as a provisional barrier, supporting keratinocyte migration and fibroblast proliferation, while its leukocyte content aids in early microbial defense [12]. Low-level erbium laser irradiation enhances epithelial cell proliferation and collagen synthesis, partly through increased TGF-β1 expression and interaction between keratinocytes and fibroblasts [15]. By reducing pro-inflammatory cytokines and promoting anti-inflammatory mediators, photobiomodulation accelerates re-epithelialization and reduces postoperative edema and pain [10]. Clinically, this results in lower plaque indices and bleeding scores, reflecting a healthier peri-implant environment that is less susceptible to biofilm-induced inflammation.

Implant stability, assessed by RFA and expressed as the ISQ, depends on both primary mechanical engagement and secondary biological stability through new bone apposition. PRF accelerates the recruitment and differentiation of osteoprogenitor cells, while low-level laser therapy enhances their metabolic activity and matrix mineralization [31]. Furthermore, the micro-explosive effects of Er:YAG irradiation may subtly modify the implant surface microtopography, promoting improved mechanical interlocking without damaging the implant threads [6]. The result is a denser peri-implant bone structure and higher ISQ values during the vulnerable early healing period, supporting earlier functional loading.

From a translational perspective, combining PRF with low-level erbium laser therapy offers a chairside, minimally invasive approach that can be easily integrated into routine implant protocols [26]. The autologous nature of PRF circumvents concerns about immunogenicity and disease transmission, and the portable laser device can be applied immediately post-operatively without additional surgical intervention [14]. By shortening healing times, reducing postoperative morbidity, and preserving crestal bone, this synergistic regimen has the potential to improve patient satisfaction and long-term implant survival rates.

The innovation of this study lies in its demonstration of the synergistic effects of combining PRF with low-energy Er:YAG laser therapy for dental implant patients. Our focus on peri-implant tissue healing, bone regeneration, and

implant stability provides valuable insights into the efficacy of this approach. By systematically assessing both short-term clinical outcomes and long-term regenerative potential in a larger cohort, we demonstrate significant improvements in BD, implant stability, and reduction in postoperative inflammation, highlighting the potential of this method to enhance patient outcomes and satisfaction in dental implant procedures.

Nevertheless, certain limitations must be acknowledged. The retrospective design of the present study limits the ability to control for confounding variables such as patient-specific healing capacity, systemic health conditions, and variations in oral hygiene. Standardizing PRF preparation and laser parameters is crucial for reproducibility across different clinical settings. Additionally, while the current findings suggest mechanistic hypotheses, direct molecular evidence - such as gene expression profiling or histomorphometric analysis - would strengthen understanding of underlying pathways. Prospective, randomized controlled trials with larger sample sizes and longer follow-up periods are needed to validate these results and refine treatment protocols.

In summary, the integration of PRF with low-level erbium laser irradiation represents a biologically sound and clinically feasible strategy for enhancing both soft and hard tissue regeneration around dental implants. By delivering a sustained reservoir of autologous growth factors and harnessing the multifaceted effects of photobiomodulation - improved cell metabolism, reduced inflammation, and enhanced scaffold dynamics. This combined approach addresses key challenges in implant dentistry. As the field evolves toward biologically driven, minimally invasive therapies, the synergy between PRF and LLLT holds significant promise for optimizing clinical outcomes and advancing the standard of care in implant rehabilitation.

Disclosure of conflict of interest

None.

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