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Original Article

SEM Analysis of Thermal Effects Induced by a 445 nm Laser on Implant Surfaces

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ABSTRACT

This laboratory study investigated how a 445 nm diode laser (Eltech K-Laser Srl, Treviso, Italy) affects the surfaces of dental implants under various power levels and irradiation methods. Fifteen new Straumann implants (Basel, Switzerland) were examined for surface changes. Each implant was divided into two regions: anterior and posterior. The anterior coronal portion was irradiated with the laser fiber positioned 1 mm away, whereas the anterior apical portion was treated with the fiber in direct contact. Posterior regions remained unexposed and served as controls. The laser was applied in two 30-second cycles, separated by a one-minute rest. Three settings were tested: 0.5 W pulsed (T-on 25 ms; T-off 25 ms), 2 W continuous, and 3 W continuous. Surface modifications were assessed using scanning electron microscopy (SEM). Results showed that the 0.5 W pulsed laser at a 1 mm distance caused no detectable changes. Continuous irradiation at 2 W and 3 W led to visible surface damage at the same distance, and direct fiber contact further intensified alterations. These findings suggest that using a 0.5 W pulsed laser with a fiber kept 1 mm from the implant may provide a safe approach for peri-implantitis therapy, avoiding damage to implant surfaces.

Keywords: Peri-implantitis, Laser, Thermal damage, Dental implants

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Introduction

In recent years, dental implants have become increasingly prominent as the primary approach for restoring masticatory function, driving extensive research into implant materials, designs, and placement techniques. Current estimates indicate that approximately 12 to 18 million implants are placed worldwide annually, reflecting the growing popularity of implant-based rehabilitation [1]. Over time, implant designs have evolved, particularly in terms of macro- and microstructural characteristics. One major advancement has been the transition from smooth to roughened surfaces to promote faster and more effective osseointegration [2, 3]. While this surface modification enhances bone integration, it also introduces a downside: roughened surfaces create favorable conditions for bacterial colonization, frequently leading to peri-implantitis—a progressive infectious and inflammatory disease of bacterial origin that causes local mucosal and bone degradation, eventually compromising peri-implant support and resulting in implant failure [4–6].

Epidemiological data suggest that approximately 24% of implant patients currently experience peri-implantitis, with new cases increasing by 2.4 to 4 million annually [1, 7]. The prevalence of this condition has prompted extensive research into treatment strategies aimed at halting disease progression and preserving implant longevity. Various therapeutic approaches have been proposed, including nonsurgical, surgical, resective, regenerative, and combined interventions [8–10]. Despite these efforts, managing peri-implantitis remains challenging, and success rates are often limited [11]. Ideally, any treatment should achieve thorough decontamination of

the implant surface by removing bacterial biofilm while preserving the implant's original surface characteristics. Studies have shown that maintaining the native surface structure supports more effective re-osseointegration and improves clinical outcomes compared to protocols that smoothen the implant surface [12].

Among emerging treatment modalities, lasers have gained attention as a potentially effective solution for peri-implantitis. Laser therapy offers several clinical advantages, including enhanced patient comfort, reduced pain, minimal need for sutures, and shorter recovery times. One key benefit is the ability of laser beams to access complex and irregular implant surfaces, which are often difficult to treat with conventional mechanical instruments, facilitating more thorough decontamination [13]. Additionally, low-intensity diode lasers used in combination with photosensitizing agents have been investigated in antimicrobial photodynamic therapy (aPDT) [14]. In aPDT, a photosensitizer is applied to the peri-implant pocket and, upon exposure to a specific laser wavelength, generates reactive singlet oxygen species that are toxic to bacteria. The topical application of the photosensitizer ensures coverage of irregular surface areas, maximizing the antimicrobial effect.

Although numerous studies have explored the use of various lasers in peri-implantitis management, no single therapeutic protocol has fully resolved the disease. Moreover, some researchers have raised concerns about potential thermal damage to implant surfaces from laser exposure [15–17]. Given these considerations, the present in vitro study aimed to investigate a novel 445 nm laser wavelength. Using scanning electron microscopy (SEM), this study evaluated the possible thermal effects of different irradiation protocols on dental implant surfaces.

Materials and Methods

This study employed a K-Laser Blu Dental device (Eltech K-Laser, Treviso, Italy), capable of emitting three different wavelengths: 445 ±5 nm (blue, visible spectrum), 660 ±5 nm (red, visible spectrum), and 970 ±5 nm (near-infrared, NIR). These wavelengths can be used individually or in combination, with software allowing selection of a single wavelength. For the present investigation, only the 445 nm (±5 nm) blue wavelength was utilized. The optical fiber had a diameter of 320 µm and was intentionally left inactive to prevent excessive narrowing of the irradiation spot, ensuring uniform energy delivery across the targeted implant areas. The laser was applied both in contact and non-contact modes, with variations in distance and power settings implemented throughout the experiment.

Fifteen new Roxolid® dental implants with SLA surfaces (Straumann, Basel, Switzerland) were used. Roxolid is a titanium-zirconium alloy composed of 85% titanium and 15% zirconium. A power analysis using a t-test yielded a value of 0.858, with $\alpha = 0.2$ and a sample size of 15 implants. The SLA surfaces exhibited macro-roughness of 20–40 µm (peak-to-peak) and micro-roughness of 2–4 µm. Based on the laser power applied, the implants were categorized into three groups (A, B, and C), each containing five implants.

For analysis, implant surfaces were divided into anterior and posterior regions. The anterior side was marked by scratching the front wall of the implant mount with a scalpel. The anterior portion was further subdivided into coronal and apical zones, with the coronal area comprising the first three spires and the apical area encompassing the last three spires. The anterior coronal regions were irradiated with the handpiece positioned 1 mm from the implant surface **(Figure 1)**, while the anterior apical regions were treated with the fiber in direct contact **(Figure 2)**. In both cases, the fiber was maintained at a 45° angle relative to the titanium surface.

Although non-contact irradiation is commonly recommended in peri-implantitis treatment protocols, maintaining a precise 1 mm distance can be challenging in clinical settings due to limited oral access and the specific anatomy of each peri-implant pocket. To better mimic real-world conditions, direct contact irradiation was also tested. Posterior regions of all implants were left untreated and served as control surfaces (CTR) **(Figure 3)**.

Figure 1. Anterior coronal region irradiation.

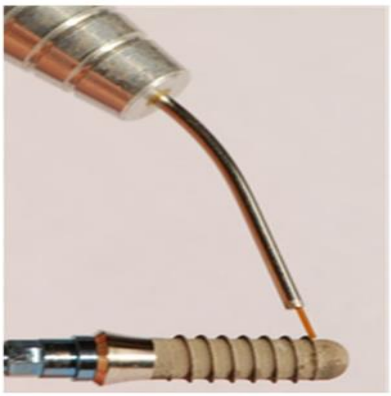


Figure 2. Anterior apical region irradiation.

Figure 3. Rear area, control surface.

The experiments were designed as clinical simulations. During laser application, the handpiece was moved manually in a back-and-forth motion at an approximate speed of 5 mm per second. The irradiation protocol consisted of two 30-second laser exposures, separated by a 60-second interval. No cooling system was applied to the targeted area during treatment. Prior to irradiating each implant surface, the tip of the optical fiber was trimmed.

To prevent surface alterations caused by sample handling, all implants were irradiated while mounted in their original holders within the packaging. Group A received pulsed wave (PW) irradiation, whereas Groups B and C were treated with continuous wave (CW) settings **(Table 1)**.

Table 1. Schematization of the irradiated areas.

	0.5 W	**2.0 W**	**3.0 W**
In-Contact	0	5	5
Non-Contact	5	5	5
Control	5	5	5
Total	10	15	15

The implants in Group A (n = 5) underwent laser treatment in a non-contact mode on their anterior coronal regions, following the "peri-implantitis" protocol of the K-Laser Blu Dental system: 0.5 W power, pulsed emission with T-on 25 ms and T-off 25 ms, and a manual scanning speed of roughly 5 mm/s.

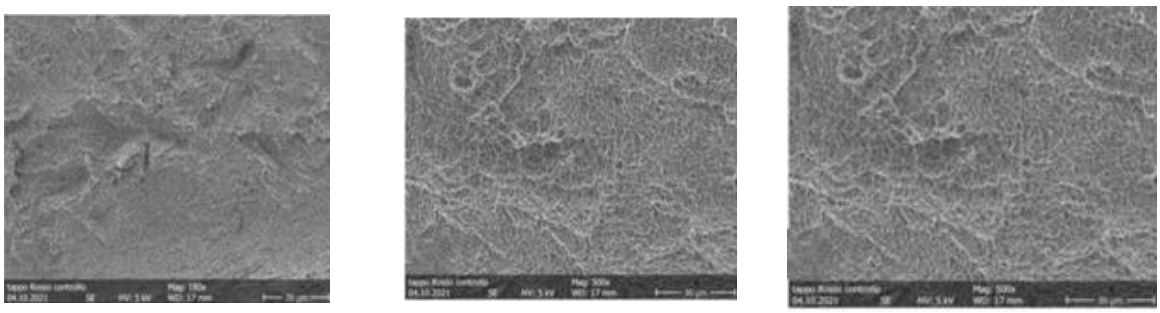
In Group B, the five implants were irradiated in non-contact mode on the coronal anterior region, while the apical anterior region was treated with the fiber in direct contact. The applied parameters were 2 W continuous wave and a handpiece movement speed of 5 mm/s.

For Group C, the anterior coronal area received non-contact irradiation, and the anterior apical region was treated in contact mode with 3 W continuous output, again moving the handpiece at approximately 5 mm/s. The higher power levels and continuous mode used for Groups B and C were selected deliberately to exaggerate thermal effects, as such settings are not safe in clinical practice due to potential soft tissue damage.

After laser application, all implants were cleaned in an ultrasonic bath with isopropanol for 5 minutes to remove oils and debris that could interfere with SEM imaging. Each implant was mounted on an aluminum stub using carbon tape and examined with a Hitachi SU4000 Field Emission SEM and a Hitachi SU3500 SEM. Imaging was performed under high-vacuum conditions at an acceleration voltage between 5 and 20 kV, capturing the irradiated areas at magnifications from 25× (scale bar: 500 µm) to 5000× (scale bar: 3 µm).

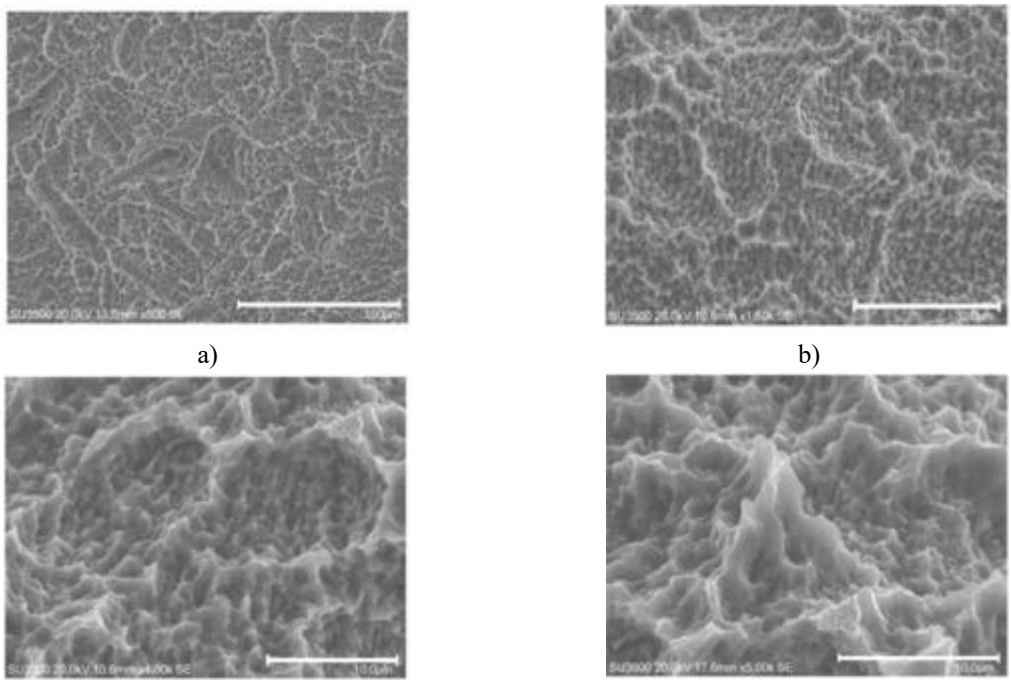
Results and Discussion

SEM images of the untreated posterior control surfaces (CTR) displayed the typical micro- and macro-porous texture of SLA-treated implants generated by combined sandblasting and acid etching **(Figure 4)**. These regions were irregular, with sharp ridges and edges. Surfaces irradiated with 0.5 W in non-contact mode appeared largely unchanged when compared to the control areas **(Figure 5)**. The laser fiber also showed no visible macroscopic alteration after completion of the irradiation procedure.



a) b) c)

Figure 4. (a-c) Scanning electron microscope images of untreated control implant surfaces. Magnifications range from 180× to 4000×.



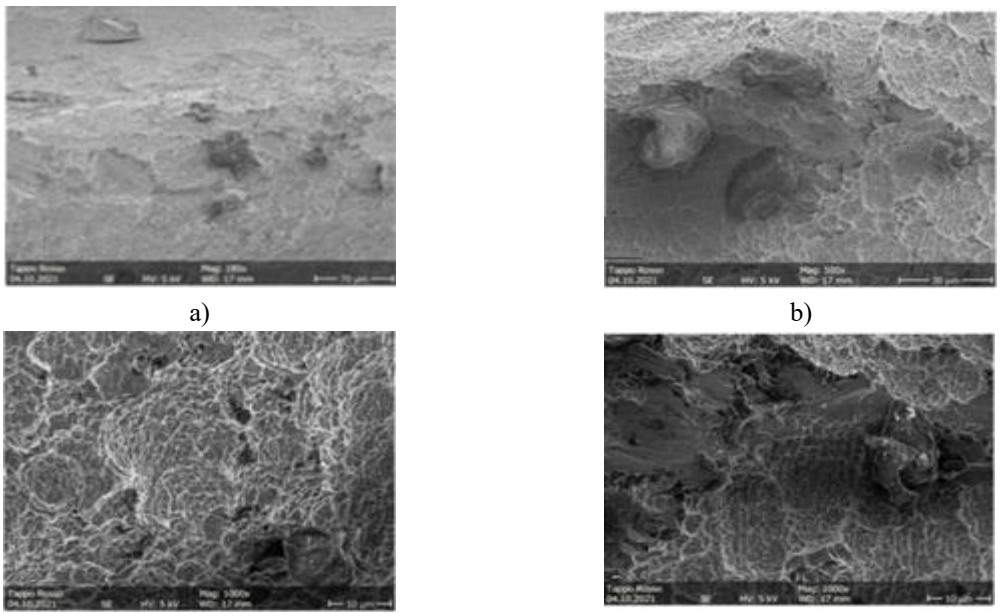
a) b)

c) d)

Figure 5. Group A. SEM images of sandblasted titanium implant surfaces after blue laser irradiation in non-contact mode, showing no detectable changes compared to untreated controls. Power: 0.5 W. Magnifications range from 500× to 5000×.

During the irradiation of implants in Groups B and C, the fiber became self-activated, likely due to the higher power settings and the dark coloration of the irradiated titanium surfaces. This caused the laser energy to be concentrated over a smaller area, producing pronounced thermal effects that were visible to the naked eye. Specifically, **Figure 6a** shows what appears to be detachment of a titanium surface fragment. **Figures 6b and 6d** illustrate loss of surface roughness caused by thermal damage to the titanium ridges. In Group B implants irradiated in contact mode **(Figure 7)**, surface alterations were even more noticeable. At 25× magnification, a reduction in surface roughness and carbonization of the optical fiber—likely resulting from elevated surface temperatures—can already be observed.

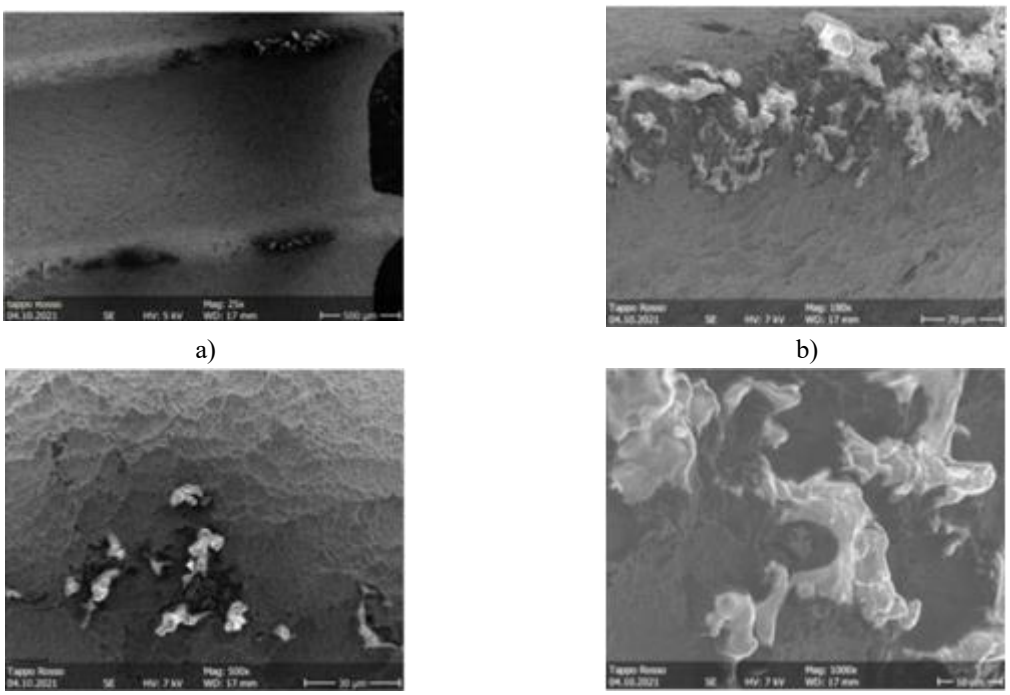
For Group C **(Figure 8)**, the laser-induced thermal effects were even more severe. **Figure 9b**, showing a coil of a Group C implant at 180× magnification compared with a control surface, highlights extensive loss of surface roughness, along with microfractures and crater-like defects, indicating substantial surface damage. Whereas Group B showed primarily localized, point-like surface changes, Group C exhibited more widespread alterations, likely reflecting the path of the laser beam. In addition to these microscopic defects, Group C implants also displayed visible color changes upon completion of irradiation. A summary of the damaged areas is presented in **Table 2**.



a) b)

c) d)

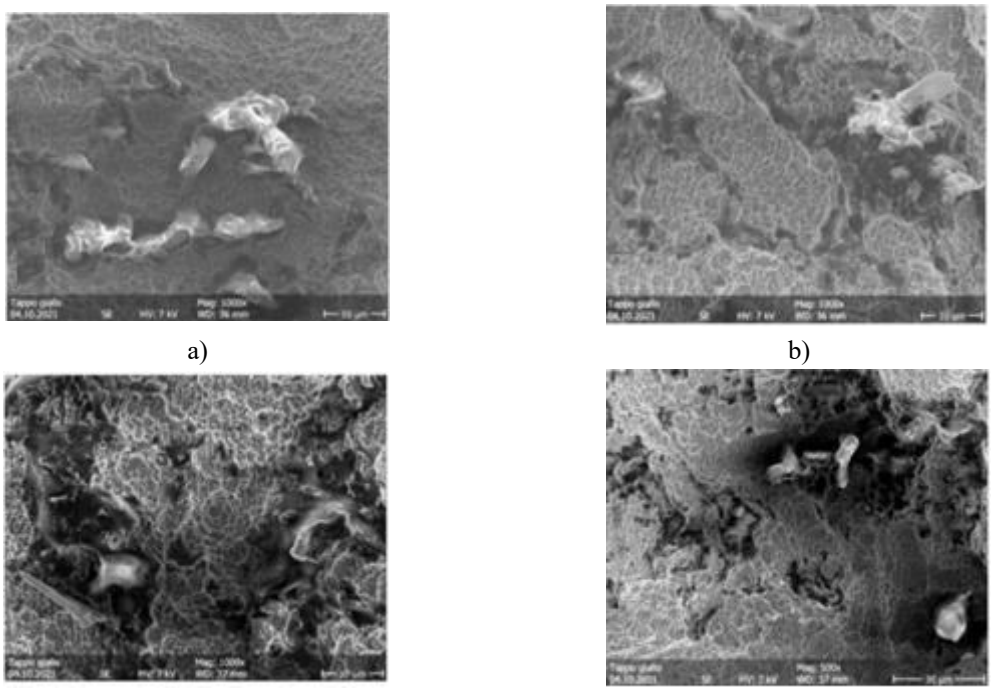
Figure 6. Group B. (a–d) SEM images of sandblasted titanium implant surfaces following blue laser irradiation in non-contact mode, exhibiting thermal effects, reduced porosity, and smoother areas. Power: 2.0 W. Magnifications range from 180× to 1000×.



a) b)

c) d)

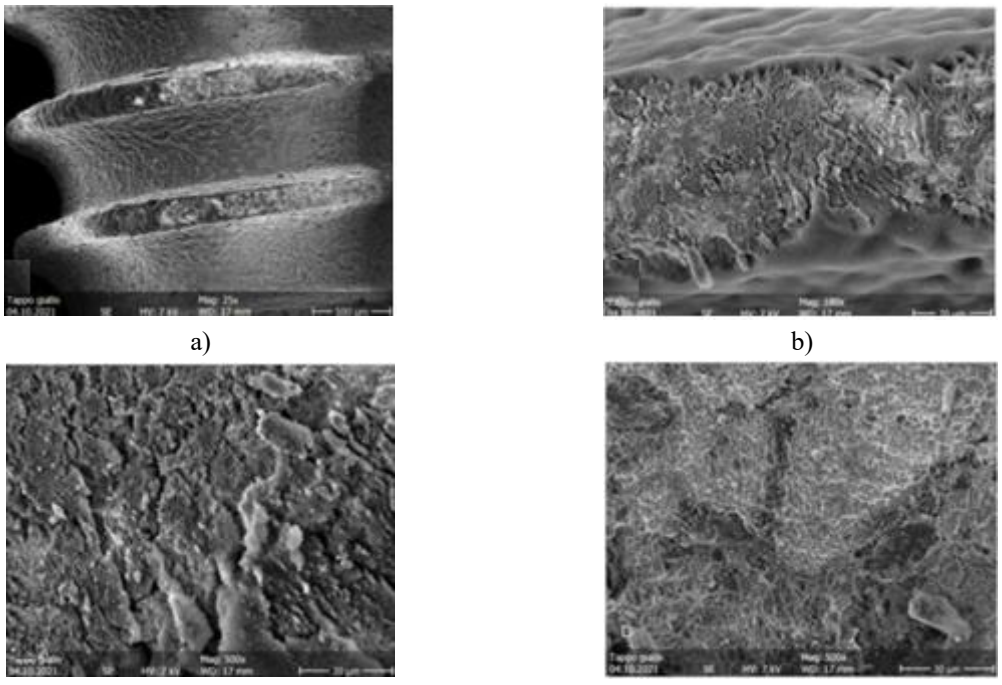
Figure 7. Group B. (a–d) SEM images of sandblasted titanium implant surfaces following blue laser irradiation in contact mode, demonstrating thermal effects and surface damage. Power: 2.0 W. Magnifications range from 25× to 1000×.



a) b)

c) d)

Figure 8. Group C. (a–d) SEM images of sandblasted titanium implant surfaces following non-contact blue laser irradiation, showing thermal effects, reduced porosity, and smoother areas. Power: 3.0 W. Magnifications range from 500× to 1000×.



a) b)

c) d)

Figure 9. Group C. (a–d) SEM images of sandblasted titanium implant surfaces following contact-mode blue laser irradiation, displaying thermal effects, microfractures, and crater-like defects indicative of extensive surface damage. Power: 3.0 W. Magnifications range from 25× to 500×.

Table 1. Schematization of the damaged areas.

	0.5 W	**2.0 W**	**3.0 W**
In-Contact	0	5	5
Non-Contact	0	5	5
Control	0	5	5
Total	0	15	15

The long-term success of dental implants largely depends on the health of the surrounding peri-implant tissues. Inflammatory conditions such as peri-mucositis and peri-implantitis, both associated with plaque accumulation, compromise these tissues. The 2017 World Workshop on the Classification of Periodontal and Peri-Implant Diseases and Conditions, Workgroup 4, provided a clear definition of these conditions and, for the first time, established criteria for defining a "healthy" implant [4].

Inflammation represents the body's natural response to microbial challenges. When plaque and calculus accumulate, the supporting tissues become inflamed, a condition known as mucositis. If left untreated through effective daily and professional hygiene, mucositis can progress to peri-implantitis, characterized by bone loss and, in severe cases, implant failure. Compared to periodontal inflammation, peri-implant inflammation often progresses more rapidly and aggressively, largely due to the absence of periodontal ligaments [18]. The primary objectives of peri-implantitis treatment are the removal of bacterial biofilm and the resolution of inflammation. Achieving these goals can promote pocket closure, reduce bleeding and swelling, halt progressive bone loss, and ultimately improve implant survival [19]. Despite these clearly defined targets, peri-implant diseases remain among the most challenging conditions for dental clinicians and researchers.

Over the past fifty years, laser devices have found numerous applications in dentistry. Thanks to their unique properties, lasers have demonstrated significant advantages across restorative dentistry, endodontics, oral surgery, periodontology, and implantology [20, 21]. The use of lasers of varying wavelengths to enhance peri-implantitis treatment outcomes has been extensively studied. Research has highlighted their antimicrobial potential, particularly against periodontal pathogens, either alone or combined with mechanical and ultrasonic debridement or air polishing [22, 23]. Historically, the most commonly employed wavelengths for such applications have included diode lasers (810–950 nm), Nd:YAG lasers in the near-infrared range, and Erbium lasers (Er:YAG and Er:YSGG) in the mid-infrared at 2940 nm and 2790 nm, respectively. For example, a split-mouth clinical trial by Moreira *et al*. involving 20 patients with periodontitis demonstrated that adjunctive antimicrobial photodynamic therapy using a low-intensity diode laser significantly reduced bacteria from the red and orange complexes compared to conventional scaling and root planing alone [24].

In addition to antimicrobial effects, low-level laser application can stimulate soft tissue regeneration around implants through a process known as photobiomodulation. This effect promotes faster wound healing, as confirmed by numerous studies [25–28].

Recently, the introduction of blue visible laser light (400–450 nm) has attracted attention in both surgical and periodontal applications. Physically, blue light interacts primarily with superficial tissues due to strong scattering by water and is strongly absorbed by hemoglobin, which has an absorption peak near 450 nm. This property makes blue lasers particularly effective for surgical procedures requiring high coagulative capacity. Furthermore, blue light exhibits specific antibacterial effects, suggesting potential utility in reducing bacterial load within periodontal pockets. Beyond these effects, blue light can modulate cellular processes by activating specific membrane receptors, such as opsins. This activation can influence nuclear gene transcription directly or indirectly via intracellular mediators, including reactive oxygen species (ROS) and nitric oxide (NO), yielding beneficial effects for the treated tissues.

Sang Woong Park *et al*. demonstrated that a 445 nm blue laser, applied in pulsed mode at low energy, can enhance local blood flow through vasorelaxation, highlighting its therapeutic potential [29].

Although the 445 nm blue laser is a relatively new device, several studies have investigated its effects on titanium implant surfaces to address the ongoing debate regarding potential surface alterations caused by laser-induced thermal effects. Malmqvist *et al*. [30] reported no detectable changes when titanium discs were irradiated for 4 minutes at 2.0 W in a non-contact mode at a distance of 1 mm. Similarly, Deppe *et al*. [31] observed no surface alterations when using either continuous-wave (CW) irradiation (0.8 W, 5 s) or pulsed-wave (PW) irradiation (3 W, 20 s, 10% duty cycle; 1 W, 10 s, 50% duty cycle). In this in vitro study, Deppe and colleagues also measured temperature increases of the implant surface during blue laser irradiation [31]. It is important to note that a rise in bone temperature of as little as 10°C for 60 seconds can cause severe and permanent structural damage, potentially compromising implant survival. Despite this, the study found that CW irradiation at 0.8 W for 5 s, as well as pulsed irradiation at 3 W (20 s, 10% duty cycle) and 1 W (10 s, 50% duty cycle), did not induce any detectable surface damage [32].

In contrast, the current study observed clear surface alterations at both 2.0 W and 3.0 W in CW mode. Irradiation at these power levels reduced implant

surface roughness, producing thermal effects on the titanium ridges, with higher power settings generating more pronounced and sometimes macroscopically visible damage. Contact-mode irradiation consistently caused greater alterations compared to non-contact mode, regardless of the power used. To date, no clinical trials have evaluated whether implants with thermally altered surfaces can successfully undergo re-osseointegration. Nevertheless, macrostructural and microstructural changes are likely to interfere with re-osseointegration if the underlying peri-implantitis is resolved.

In this study, only implants irradiated twice for 30 seconds at 0.5 W in non-contact mode, with a 1 mm distance, showed no detectable surface alterations. Based on these results, the K-Laser manufacturer recommends 0.5 W as the standard power setting for peri-implantitis treatment. Among the power levels tested in this study, 0.5 W appears to be the safest and most clinically applicable.

A further concern with higher-power blue laser use was fiber carbonization on the implant surface. This self-activation within the peri-implant pocket may cause a local temperature rise, potentially triggering inflammation in peri-implant tissues and promoting plaque accumulation.

Other studies in the literature have also reported surface changes on titanium discs and implants using various laser parameters. Romanos *et al*. [33] found that Nd:YAG lasers (1064 nm) at 2.0 and 4.0 W in contact mode produced thermal damage to titanium surfaces, whereas diode lasers (980 nm) at 5.0, 10.0, and 15.0 W in continuous contact mode did not. Lee *et al*. [34] reported surface alterations with Er:YAG lasers (2940 nm) at 1.4 and 1.8 W in contact for 1 minute, but not at 1.0 W. Stubinger *et al*. [35–37] observed surface damage using Er:YAG lasers at 3.0 and 5.0 W (300–500 mJ/pulse) for 10 s in contact, while no alterations occurred at 1.0 W. Similarly, CO_2 lasers (10,600 nm) at 2.0, 4.0, or 6.0 W and diode lasers (810 nm) at 1.0 or 3.0 W in non-contact mode did not cause surface changes.

A limitation of this in vitro study is the lack of implant temperature monitoring during irradiation, which could provide valuable information on thermal effects.

Further investigations are needed to fully understand the potential role of lasers in peri-implantitis management. Comparative studies assessing different wavelengths, power settings, and irradiation modalities under standardized conditions are essential to identify optimal protocols. Such research would allow clinicians to maximize the therapeutic potential of lasers while ensuring safe and effective treatment for patients.

Conclusion

Based on the analysis of the magnified images, it was observed that implants irradiated with 2.0 W and 3.0 W—whether with the fiber in contact with or at a distance from the implant—exhibited surface alterations, including loss of porosity, microfractures, and crater-like defects, indicating severe surface damage. In contrast, using a 0.5 W pulsed laser (T-on 25 ms; T-off 25 ms) with an inactivated fiber positioned 1 mm away from the implant did not produce any detectable surface changes. This suggests that this setting may be considered safe for preserving the integrity of the implant surface while allowing further research into peri-implantitis treatment. Furthermore, contact-mode irradiation and higher power levels caused more pronounced surface alterations than non-contact irradiation and lower power. Additional microbiological studies are necessary to confirm the effectiveness of this approach against the pathogens responsible for peri-implantitis.

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Conflict of Interest: None

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