Surface Modification of a Titanium Implant Using Nd:YAG Laser: an In-Vitro Study

Varun Keskar1 , V.Vyshna1,a)

1Varun Implant Centre, Haryana, India

Corresponding Author: a)[vyshnavibds@gmail.com](mailto:vyshnavibds@gmail.com)

**Abstract:** Given the recent strides in dental implantology, there exists a profound biomedical, technical, and foundational curiosity surrounding the alterations made to the surface of titanium implants. This investigation seeks to evaluate and draw comparisons regarding the modifications in surface topography and morphology of a titanium implant subsequent to exposure to a spectrum of Nd: YAG laser wavelengths.Employing a conventional metallurgical process, 10 titanium implants with standard rectangular dimensions measuring 12 mm by 12 mm by 4 mm were fabricated. The irradiation of samples was carried out using a quartz lens with a focal length of 12 cm. The implants were arbitrarily divided and allocated into two sets, each subjected to irradiation using Nd: YAG lasers with distinct wavelengths.Surface topography and attributes were examined and visualized through the application of scanning electron microscopy, atomic force microscopy, and optical microscopy. Profilometry was employed for the scrutiny of the ablated region's configuration.Post-experimentation, the ensuing observations can be succinctly outlined as follows: (i) manifestation of discernible nano-scale patterns at a more distant periphery; (ii) titanium ablation within the central region; and (iii) titanium ablation within the central zone. The threshold for damage in the interaction between Nd: YAG (532 nm) and titanium was computed as 0.5 J/cm2, notably lower than the indistinct threshold associated with laser radiation at 1064 nm, which stands at 0.8 J/cm2.The application of laser activity at 1064 nm manifests discernible damage perimeters on the surface of the titanium implant; however, at 532 nm, these perimeters appear somewhat dispersed. Furthermore, the surface roughness of titanium is exacerbated by the influence of each laser wavelength. The presence of plasma in front of the implants indicates a relatively elevated temperature generated above the surface, contributing to a sterilizing effect and fostering conditions free from contaminants.

**Keywords**: Dental Implants, Laser induced damage, Surface alterations, Nd: YAG laser

# INTRODUCTION

Investigating laser-based surface modification in titanium proves intriguing from fundamental, technological, and biological perspectives[(Rajeshkumar & Lakshmi, 2021; Sivakumar et al., 2021)](https://paperpile.com/c/d714yC/eaCzj+dRGXG). Titanium boasts outstanding chemical and physical attributes, characterized by a high melting point, elevated specific-weight ratio, and remarkable resistance to corrosion and erosion [(Freitas & Simões, 2015)](https://paperpile.com/c/d714yC/bdSa). Consequently, this material holds significant appeal for diverse applications spanning nuclear, marine, and medical space technology. Owing to their remarkable biocompatibility within the human body, titanium and its alloy-based implants are extensively utilized in the medical sector[(Rosentritt et al., 2024)](https://paperpile.com/c/d714yC/bOMc). Their applications extend to joint replacements in diverse anatomical regions, such as the hip, knee, shoulder, wrist, and spine[(Miserendino & Pick, 1995; Rosentritt et al., 2024)](https://paperpile.com/c/d714yC/bOMc+7Ok7). In the realm of dentistry, titanium implants serve a variety of purposes, including the replacement of missing teeth [() et al., 2003)](https://paperpile.com/c/d714yC/CjJV). The use of Ti6Al4V is prevalent in alloy-based dental implants [(Baydan & Soylu, 2024)](https://paperpile.com/c/d714yC/QZi7), whereas CP-grade titanium remains a common choice for general titanium implants [(Franzen, 2011)](https://paperpile.com/c/d714yC/YVS1).The deliberate initiation of osseointegration within the surrounding host tissues is widely acknowledged to hinge on the interaction between cells and tissues with the implant[(Miserendino & Pick, 1995)](https://paperpile.com/c/d714yC/7Ok7). The efficacy of this interaction is also influenced by the state of the implant's surface [(Awooda, 2023)](https://paperpile.com/c/d714yC/9qzj).Ensuring the absence of contaminants on the implant surface is imperative, and given the significance of roughness in tissue integration, it stands as a favorable morphological characteristic . Notably, a textured surface promotes the growth of bone around the implant [(Franzen, 2011)](https://paperpile.com/c/d714yC/YVS1). Laser treatment emerges as one of the most effective techniques for enhancing the surface roughness of a titanium implant [(Mathevanan et al., 2023)](https://paperpile.com/c/d714yC/SR4T).Studies on the interaction of laser beams with titanium have generally drawn more attention, particularly in the past ten years[(Chokkattu et al., 2023; Dharman et al., 2023; Govindaraj & Shanmugam, 2023)](https://paperpile.com/c/d714yC/ZVW3w+FYbnO+5GrT0). Thus far, Nd: YAG serves the pre-mentioned objectives [(Misch, 2014)](https://paperpile.com/c/d714yC/zs2n). The requirements are also satisfied by different Excimer systems , titanium-sapphire , TEA carbon dioxide , CW carbon dioxide .[(Barbič et al., 2024; Misch, 2014)](https://paperpile.com/c/d714yC/zs2n+gPip) In contrast to the nanosecond realm , the chemical relationship of a Nd: YAG beam in the picosecond time range with titanium has not been sufficiently described in the literature[(Janani et al., 2021; Kachhara et al., 2021; Subramanian et al., 2023)](https://paperpile.com/c/d714yC/TCWuS+vDmU7+G55xf). This work investigates the effects on a titanium implant's surface of a picosecond laser therapy operating in the 532 nm and 1064 nm wavelengths[(Gandhi et al., 2021; Katyal et al., 2023; Priyadharshini et al., 2023)](https://paperpile.com/c/d714yC/P9F0L+8SRh0+XLNKo). At both wavelengths, titanium's morphological surface modifications received particular attention.[(Barbič et al., 2024; McQuillan & McQuillan, 1956; Misch, 2014)](https://paperpile.com/c/d714yC/zs2n+gPip+r8i2)The purpose of this work was to examine the surface topography and morphology changes of titanium implants following exposure to two distinct Nd: YAG laser wavelengths. The null hypothesis stated that after being exposed to two distinct Nd: YAG laser wavelengths, there would be no change in the surface morphology of the implant surface.

# MATERIALS AND METHODOLOGY

The Institutional Review Board gave its approval for this study, which was conducted at the Utilizing G\*Power 3.1.9.3 for Mac OS X®[(Erdfelder et al., 1994)](https://paperpile.com/c/d714yC/GUzO), the sample size was determined by consulting data from an earlier publication[(Erdfelder et al., 1994; Sotova et al., 2023)](https://paperpile.com/c/d714yC/GUzO+L54C) . Assuming a normal distribution, an effect size (dz=1.5004), a power of 0.95 (1−β error probability), and a significance of 0.05 (α). For this study, a sample size of 5 per group was finalized.Group 1 was to be irradiated using a 532 nm laser whereas Group 2 was planned to be irradiated using a 1064 nm laser

## Sample Preparation

Employing a conventional metallographic process, the fabrication of the titanium implant surface was executed, encompassing sequential steps of drying, washing, and polishing. The dimensional parameters of the rectangular sample adhered to standard measurements, typically measuring 10 mm by 10 mm by 4 mm. The surface roughness of the sample, gauged using AFM, was appraised to be ≤ 0.6mm. It is noteworthy to mention that the samples utilized in this inquiry closely mirrored those detailed in the cited reference article [(Sotova et al., 2023)](https://paperpile.com/c/d714yC/L54C).

# Methodology for laser irradiation

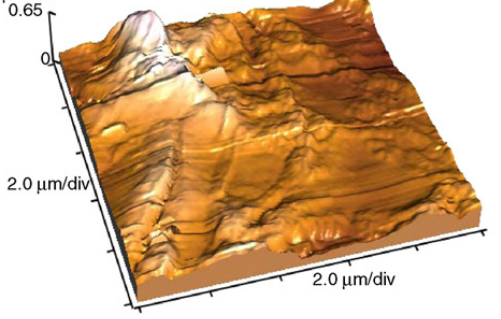
To subject the samples to irradiation, a laser beam was directed through a quartz lens with a focal length of 12 cm. The laser beam operated in the standard transverse mode during the radiation process. The incidence of the laser beam on the surface occurred at a 90-degree angle. The irradiation was conducted in an air environment, maintaining standard levels of relative humidity and a pressure of 1013 mbar.The laser employed in this study was the Quanta System Srl. - Solbiate Nd: YAG system [(Gulati, 2023)](https://paperpile.com/c/d714yC/1SRP), specifically the SYL P2 model. This system comprises a laser oscillator, an amplifier, and a nonlinear crystal (KD\*P). To generate pulses with a duration of approximately 40 ps, a saturable absorber dye and a standing wave modulator were incorporated. The laser operated at a typical repetition rate of 2 Hz. Depending on the experimental requirements, the irradiation wavelength was selectively set to either 1064 or 532 nm.

## Assessment of surface changes

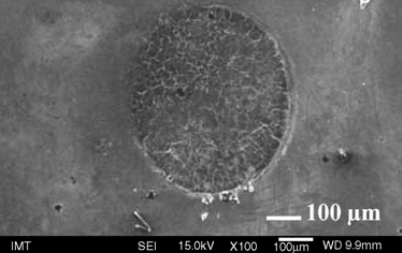
The titanium implant samples were characterized using a variety of analytical methods both before and after laser irradiation.Employing an X-ray diffractometer, the identification of crystal phases was conducted. The assessment of surface morphology was undertaken through the utilization of optical microscopy, scanning electron microscopy, and atomic force microscopy. To scrutinize the surface compositions of the targets, an energy-dispersive analyzer was coupled with the SEM..With a contact-type profilometer, the surface roughness (Ra, μm) of twelve samples from each group was measured for three areas (two at the margins and one in the center) using a maximum applied force of 0.75mN. The stylus radius was 2µ with an angle at the tip of 60°. To assess each specimen's general surface characteristics, the mean value was computed.

# RESULTS

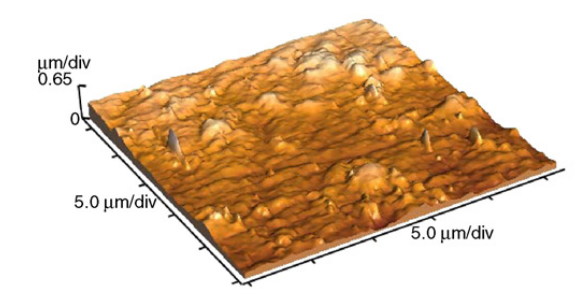
Prior to laser irradiation, X-ray diffraction analyses were employed to confirm the crystalline structure of titanium. The analysis revealed distinct (1 0 1) and (0 0 2) orientations within the hexagonal structure, indicative of the titanium a-phase. Typically, the surface of the titanium implant exhibited a metallic hue. Preceding the irradiation, elemental analysis using EDS was conducted on the sample surface.Per the revelations, the titanium composition in the sample accounted for 93.42%, with oxygen (4.32%), carbon (2.17%), and aluminum (0.09%) collectively constituting the remaining 100%, where all percentage data are duly weighted. The comprehensive elemental analysis underwent standardization. An exploration into the morphological alterations on titanium implants induced by lasers has been undertaken, disclosing that these changes hinge on the inherent characteristics of the laser beam. Such attributes encompass energy density, peak power density, pulse duration, the cumulative count of pulses, and wavelength. Throughout the experimental process, the energy densities of laser radiation at 1064 nm and 532 nm were determined to be 4.0 and 13.6 J/cm2, respectively.The alterations on the surface can be succinctly encapsulated as follows: the central portion of the titanium undergoes ablation, with the proximate periphery exhibiting a recurrent structure reminiscent of waves, and the remote periphery showcasing a unique nano-scale architecture. The introduction of a higher accumulation of laser pulses resulted in a conspicuous microstructure resembling waves, notably observable within the range of 50 to 100 pulses, for instance. In this scenario, the central domain of the affected region exhibited an intensified depth. An increased aggregation of laser pulses, ranging between 50 and 100 pulses, for instance, resulted in the conspicuous development of a microstructure resembling waves. Under these conditions, the central sector of the damaged area exhibited a heightened depth. The defined limit for the interaction between titanium and Nd: YAG (532 nm) was computed to be approximately 0.6 J/cm2, a magnitude notably lower than the corresponding value (0.9 J/cm2) for laser irradiation at 1064 nm.



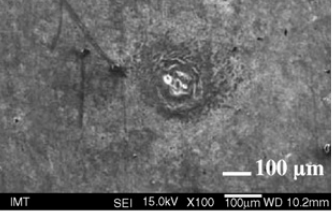
**Figure 1:** Titanium surface without irradiation



**Figure 2:** Surface topography of titanium after irradiation by 1064 nm laser



**Figure 3:** SEM at 1064 nm irradiation



**Figure 4:** Surface topography of titanium after irradiation by 532 nm

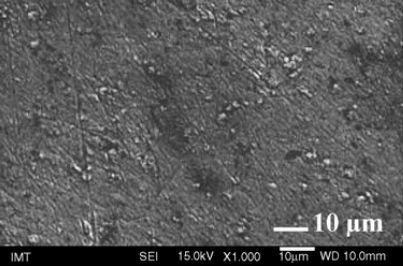


Figure 5: SEM at 532 nm irradiation

# DISCUSSION

The absorption of laser energy by metals, titanium included, is predominantly undertaken by free electrons [(Shi et al., 2023)](https://paperpile.com/c/d714yC/F1hZ). The electron subsystem undergoes thermalization due to the absorption of radiation energy within the skin layer[(Pavithra et al., 2023; Shenoy et al., 2023; Thomas & Jain, 2023)](https://paperpile.com/c/d714yC/csDkF+ovAWg+gQUKQ). This process results in the transfer of heat into the metal, and the lattice receives energy through electron thermal diffusion.Disregarding thermal dispersion linked to laser pulses with LRED values surpassing the allowable damage threshold is impractical[(Doshi et al., 2023; Lampl et al., 2023; Pandiyan et al., 2023)](https://paperpile.com/c/d714yC/fRwRj+qZ3FG+r6w1b). The diverse effects induced on the target or implant, contingent upon LRED values, encompass ionization of vaporized material, vaporization of molten components, melting, and dissociation, among other outcomes [(Abdulla et al., 2023; Shi et al., 2023)](https://paperpile.com/c/d714yC/F1hZ+viB0).In our experiments, titanium underwent exposure utilizing two distinct energy density laser regimes, resulting in the emergence of the following features and alterations: (i) Under the influence of higher LRED radiation at 23.8 J/cm2, an accumulation of molten material was generated on the designated surface and ejected towards the molten metal in proximity to the edges.This phenomenon transpired due to the assimilated energy surpassing the remaining heat. The circumstances remained akin to employing one or five pulses; however, in the latter scenario, there was an augmentation in the depth of the irradiated region. (ii) Subjecting the material to radiation with a diminished laser radiation energy density at 4.0 J/cm2 led to a reduced pace of ablation [(Fang et al., 2024; Ma et al., 2023; Shu et al., 2023)](https://paperpile.com/c/d714yC/ANWw+Qnjk+tTiz).At a wavelength of 532 nm, the titanium implant surface underwent changes when subjected to thirty laser pulses at an energy density of 13.6 J/cm2. Cunha et al. [(Cunha et al., 2022)](https://paperpile.com/c/d714yC/rlfg) noted that subjecting titanium to 30 cumulative laser pulses led to a more pronounced modification on the surface compared to the effects observed with five pulses.The alterations on the surface can be encapsulated as follows: (i) The central region exhibits the manifestation of titanium; (ii) in the proximate periphery, a recurring structure reminiscent of waves becomes apparent; and (iii) in the more distant periphery, there is the visibility of a unique nano-scale structure(Rafi et al., 2024). Notably, an intensified wave-like microstructure was engendered when the cumulative pulse count of the laser was elevated to a range of 50-100 pulses (Tuluwengjiang et al., 2024). Under these circumstances, the central sector of the afflicted region displayed an augmented profundity [(Ramsundar et al., 2023; Rieshy et al., 2023; Singh et al., 2023)](https://paperpile.com/c/d714yC/6tgS9+guQ6l+x1nwL).The structural modifications, notably the emergence of nano-grains and micro-cracks, primarily resulted from the rapid heating and cooling cycles affecting the surface layer of the target or implant .[(Cunha et al., 2022; Saran et al., 2023)](https://paperpile.com/c/d714yC/rlfg+GTf9) Additionally, in this scenario, a minor quantity of material was expelled towards the periphery, inducing an instantaneous rise in the roughness of the target or implant . An observable phenomenon of spark-like plasma materialized in front of the sample during both the initial and successive pulses of the Nd: YAG laser following its interaction with titanium.[(Hindy et al., 2017)](https://paperpile.com/c/d714yC/lvbu)Employing an Nd: YAG laser on the titanium surface resulted in considerable melting and impairment of both the coating and micromachined surface. The recent findings from Park et al[(Park et al., 2006)](https://paperpile.com/c/d714yC/Zb7t)., illustrating heightened absorption in metallic surfaces treated with Nd: YAG lasers, underscore the substantial hazard associated with the utilization of these lasers in soft tissue peri-implant procedures.In instances where Nd: YAG lasers are employed, there exists a possibility of inducing heat-induced injury leading to necrosis in the peri-implant tissues and the supporting bone adjacent to endosseous implants. As a result, the utilization of Nd: YAG lasers is not advised for treating peri-implantitis or for hyperplastic soft tissue gingivectomy, commonly known as the second-stage surgery for submerged endosseous implants.[(Guarnieri et al., 2020)](https://paperpile.com/c/d714yC/6faH)The Nd: YAG laser exerted a substantial influence on the surface, and the extent of damage exhibited a direct correlation with the applied power. Evident areas of melting on the surface were observed, posing potential ramifications on the mechanical strength of the implant, notably in terms of tensile or bending fatigue strength. Consequently, the clinical application of Nd: YAG lasers poses notable challenges. Moreover, there is the potential for the laser to induce osteolysis or inflict damage on the adjacent bone tissue[(Fahlstedt et al., 2021)](https://paperpile.com/c/d714yC/xM44).The investigation was conducted extracorporeally, and the application of the device within an authentic oral environment would pose formidable challenges. The efficacy of Nd: YAG lasers is contingent on their absorption into intracellular proteins, suggesting optimal functionality in regions where pigments such as melanin are prevalent.[(Fahlstedt et al., 2021; Yang et al., 2020)](https://paperpile.com/c/d714yC/xM44+79Ci)At a wavelength of 532 nm, the interaction between titanium and Nd: YAG was appraised to possess a damage threshold of 0.6 J/cm2, a magnitude inferior to the corresponding threshold for laser radiation at 1064 nm (0.9 J/cm2). This discrepancy is ascribed to the diminished reflectance of titanium , standing at 0.55 for longer wavelength radiation and 0.49 for shorter wavelength radiation . Consequently, there ensues an enhancement in the coupling between the laser and the target, thereby diminishing the adverse effect threshold at 532 nm.The heightened presence of oxygen in the irradiated region compared to the non-irradiated section implies potential oxidation of the titanium sample. In the non-irradiated zone, the initial oxygen concentration stood at 4.34%. Broadly speaking, the incorporation of titanium oxide(s) onto the implant surface is particularly advantageous for various reasons: (i) the arrangement and constitution of the oxides exhibit resilience against corrosion on the implant specimen, (ii) titanium oxides can influence the adhesion properties of the implant surface, and (iii) the oxidation process of a titanium-made implant holds the potential for fortification and enhancement of damage resistance [(Jones et al., 2023)](https://paperpile.com/c/d714yC/Jvua).

# CONCLUSION

Upon laser irradiation at 1064 nm, the implant surface distinctly exhibits an eroded perimeter, whereas at 532 nm, the effects are somewhat diffused. Additionally, both laser wavelengths contribute to an augmentation in the surface roughness of titanium.Solely the 532 nm-powered radiation exhibited microscopic structures reminiscent of waves, while the 1064 nm irradiation seemed to be linked with a hydrodynamic feature at the perimeter, involving resolidified material droplets. Exceptional implant surfaces can be acquired and processed as damage can transpire almost instantaneously on a titanium surface.The existence of plasma in the proximity of the implant edges signifies elevated temperatures above the surface, thereby fostering a microbe-free environment and concurrently serving as a disinfective mechanism.

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