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REVIEW ARTICLE

# The use of laser therapy for dental implant surface decontamination: a narrative review of in vitro studies

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**Abstract** The aim of this narrative review was to critically evaluate in vitro studies assessing the efficacy of lasers in the bacterial decontamination of titanium implant surfaces. The MEDLINE, Web of Knowledge and Embase electronic databases were used to search for articles relating to the use of lasers in the bacterial decontamination of titanium specimen surfaces using predetermined search statements. Clinical studies, case reports, case series, review articles and animal models were excluded. Study selection was carried out independently and then cross-checked by two authors through abstract viewing. Eighteen articles were selected for full-text analysis. Erbium-doped yttrium–aluminium–garnet lasers had a wide range of powers capable of inducing bacterial decontamination. While carbon dioxide and gallium–aluminium–arsenide diode lasers demonstrated the ability to produce bacterial decontamination, the bacterial sensitivity to each varied depending on the species involved. There is no concensus on the laser type or settings that are optimal for bacterial decontamination of titanium implant surfaces as studies employ various test specimens, contamination methodologies, irradiation settings and protocols, and outcome measures resulting in limited study comparability. More investigations are required to provide guidelines for the use of laser therapy in the decontamination of implant surfaces.

**Keywords** Dental implants · Lasers · In vitro · Decontamination

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## Introduction

Peri-implantitis is an infectious inflammatory disease associated with bleeding, suppuration and the loss of supporting bone around functioning osseo-integrated implants [1]. The presence of gram-negative anaerobic biofilm on the implant surface has been implicated in the aetiology of peri-implantitis [2].

The high prevalence, ranging from 16 to 47.1 %, of peri-implantitis has led researchers to investigate a number of therapeutic interventions for implant surface decontamination [3, 4]. These include mechanical debridement, chemical disinfection, sustained release antibiotics, and regenerative and resective surgical therapy. Recent studies have indicated that there is no gold standard for the management of peri-implantitis with most of the modalities being incapable of achieving complete removal of inflammatory tissue, bony defect debridement or implant surface decontamination [5]. Current therapies offer limited clinical improvements and have almost no microbiological improvements 6 months after treatment [5].

Laser irradiation has been suggested as a strategy for surface decontamination in the treatment of peri-implantitis. Multiple lasers, including erbium-doped yttrium–aluminium–garnet (Er:YAG), carbon dioxide ($CO_2$), gallium–aluminium–arsenide (GaAlAs) diode, neodymium-doped yttrium–aluminium–garnet (Nd:YAG) and erbium- and chromium-doped

yttrium–scandium–gallium–garnet, have been evaluated. Before applying an irradiation protocol at the patient level, in vitro testing is necessary to determine the optimal settings for decontamination. Currently, there is no standard recommendation pertaining to the laser type, settings or irradiation protocol for the treatment of peri-implantitis. In order to meet this objective, it is necessary to analyse the available literature in order to develop a set of evidence-based settings and protocols for laser irradiation.

As such, it is the aim of this narrative review to critically evaluate in vitro studies assessing the efficacy of lasers in the bacterial decontamination of titanium implant surfaces.

## Methodology

### Study selection

The MEDLINE, Web of Knowledge and Embase electronic databases were used to search for articles relating to the use of lasers in the bacterial decontamination of titanium specimen surfaces. Four literature searches were carried out using the following key words:

1. (peri-implantitis or periimplantitis or peri implantitis or periimplant or peri-implant or periimplant lesions or peri-implant lesions) and (laser or lasers)
2. (contaminated or contamination or infected or infection) and (titanium or implant or implants) and (laser or lasers)
3. (in vitro or model or trial) and (contaminated or contamination or infected or infection) and (titanium or implant or implants) and (laser or lasers)
4. (in vitro or model or trial) and (decontaminated or decontamination or disinfected or disinfection) and (titanium or implant or implants) and (laser or lasers)

The search parameters included all studies reported in English, published within the past 20 years, current to 8 February 2012. Abstracts were read and in vitro studies investigating the effect of laser therapy in the bacterial decontamination of titanium specimens were selected. Clinical studies, case reports, case series, animal studies and review articles were excluded.

The search on both databases was carried out independently by MSK and AK. Using the search criteria, each author selected articles to be included in the review. The selections were cross-checked and any discrepancies were resolved by viewing the full text, reviewing the predetermined criteria and seeking the opinion of the third author, ATS. During the independent selection process, if uncertainty regarding the decision to include a paper was encountered, each of the authors was capable of gaining a second opinion via consulting ATS.

### Data abstraction

Following the cross-checking of the selected studies, a Microsoft Excel spreadsheet to homogenise the data abstraction categories was formulated. Specimen data collected included titanium grade, geometric dimensions and surface type. Contamination protocol and laser settings including laser type, power, tip, irradiation distance, duration, angle and mechanism were recorded. Finally, the decontamination evaluation mechanism and outcomes as well as observed morphological alterations were recorded.

Independent data abstraction was carried out by MSK and AK followed by a cross-checking of the collated data. Any discrepancies or deficiencies in the data were resolved through combined reviewing of the article full text.

### Data analysis

A qualitative comparison was carried out to examine the level of implant surface decontamination achieved by each laser.

## Results

Initial search results gave a total of 419 articles through the MEDLINE database, 952 articles through the Web of knowledge database and 531 articles through the Embase database. Eighteen articles were selected for full-text analysis [6–23]. The potential of lasers to decontaminate titanium implant surfaces was confirmed by all the studies [6–20, 22, 23] except Block et al. [21].

The majority of the studies evaluated the decontamination outcome using either scanning electron microscopy (SEM) [9, 10, 14, 18, 19], counting the colony forming units (CFU) [6, 8, 12, 20–23] or a combination of these techniques [11]. Less common evaluation techniques included bacterial smears [7], light microscopy images to evaluate clean implant surface percentages [13, 15–17] and photometric XTT–formazan evaluations [19].

A variety of settings were investigated for the use of the Er:YAG laser in inducing surface decontamination (Table 1). Decontamination efficacy was dose-dependent with values ranging from 59 % following irradiation with 80 mJ/pulse at 5 Hz [20] to 99.94 % following irradiation with 120 mJ/pulse at 10 Hz [11]. Tosun et al. [20] demonstrated that using Er:YAG laser in the very short pulse (VSP) mode gave greater bactericidal activity at any given power than the short pulse (SP) mode but that 100 % bactericidal effects were only consistently achieved at 90 mJ/pulse at 10 Hz in SP mode.

Similarly, the $CO_2$ laser showed dose-dependent decontamination efficacy with values ranging from 68 % following

**Table 1** Er:YAG laser specifications used in in vitro studies evaluating the decontamination of titanium specimens with analysis mechanisms and key outcomes

| Study | Wavelength ($\lambda$) | Tip (μm) | Duration (s) | Mode | Power | Decontamination potential |
|---|---|---|---|---|---|---|
| Kreisler et al. [11] | 2,940 nm | Optical fibre (540 μm) | 60 | Pulsed | 60 mJ/pulse, 10 Hz<br>120 mJ/pulse, 10 Hz | CFU—bactericidal reduction:<br>60 mJ: 99.51 % (SA), 98.39 % (HA), 99.6 % (TPS)*<br>120 mJ: 99.92 % (SA), 99.85 % (HA), 99.94 % (TPS)*<br>SEM: 120 mJ<br>SA: sparse distribution of cells |
| Matsuyama et al. [13] | NR | NR | NR | Pulsed | 30 mJ/pulse, 30 Hz<br>50 mJ/pulse, 30 Hz<br>100 mJ/pulse, 30 Hz<br>200 mJ/pulse, 30 Hz | Stereomicroscopic imaging: less effective removal of calculus when compared with ultrasonic scaling |
| Schwarz et al. [15] | 2,940 nm | Cone-shaped glass fibre | 336 | Pulsed infrared | 100 mJ/pulse (12.7 J/cm$^2$), 10 Hz=85 mJ/pulse at tip | Light microscopy imaging:<br>Laser: CIS (94.2 %) and RPB (5.8 %),<br>Ultrasonic: CIS (63.2 %) and RPB (36.8 %)<br>Plastic curette + CHX: CIS (38.9 %) and RPB (61.1 %)* |
| Quaranta et al. [18] | 2,940 nm | Periodontal glass fibre (600 μm) | 16 | Pulsed | 30 mJ/pulse; 10 Hz<br>20-μs pulse duration | SEM:<br>Decontamination values: 76.2 % (machined), 90.9 % (TPS), 98.3 % (sandblasted/acid etched)*<br>Minimal residual bacterial presence in all groups |
| Sennhenn-Kirchner et al. [19] | 2,940 nm | Sapphire (800 μm) | 80 | Pulsed | 100 mJ/pulse, 10 Hz from laser which gave these at the tip: 12.0 J/cm$^2$, 10 Hz and 15.2 J/cm$^2$, 10 Hz | Photometric XTT–formazan analysis of mitochondrial dehydrogenase activity:<br>Irradiated specimen, 0.00<br>Non-irradiated specimen, 0.25*<br>SEM: near complete removal of fungal cells |
| Tosun et al. [20] | 2,940 nm | R02-C-111 handpiece | 10 | SP VSP | 80 mJ/pulse, 5 Hz<br>90 mJ/pulse, 5 Hz<br>80 mJ/pulse, 10 Hz<br>90 mJ/pulse, 10 Hz | CFU—bacterial reduction:<br>SP: 80 mJ/pulse at 5 Hz, 59 %; 90 mJ/pulse at 10 Hz, 100 % (only mode to give 100 % bactericidal effects)<br>VSP: 80 mJ/pulse at 5 Hz, 91 %; 90 mJ/pulse at 10 Hz, 99–100 % |

*CIS* clean implant surface (in percent), *RPB* residual plaque biofilm (in percent)

*$p<0.01$ (statistically significant differences)

irradiation with 2–4 W (10 ms/pulse, 20 Hz) to 100 % following irradiation with 6 W (20 ms/pulse, 20 Hz) [20] (Table 2). Kato et al. [8] reported that *Streptococcus sanguinis* has more resistance to $CO_2$ irradiation than *Porphyromonas gingivalis* when a range of energies from 15 to 40 J was examined; these findings were consistent with the other literature [22].

The GaAlAs diode laser yielded variable decontamination results with the efficacy increasing in a dose-dependent manner similar to the Er:YAG and $CO_2$ lasers (Table 3). The decontamination capacity increased from 45 % at 0.5 W to 99.9 % at 2.5 W [12], but multiple studies reported that complete bacterial elimination is not possible [12, 19]. However, Tosun et al. [20] displayed 100 % decontamination at powers as low as 1 W; this was consistent with Sennhenn-Kirchner et al. [23] where mean bacterial reduction ranges were between 94.67 and 100 %. *Enterococcus faecalis* and *S. sanguinis* were more resistant to GaAlAs diode laser irradiation than *P. gingivalis* [6, 22]. This is similar to the $CO_2$ laser where *P. gingivalis* was more susceptible to irradiation compared to other microbial species.

The Nd:YAG laser gave variable decontamination values with studies showing incomplete elimination of the microbial organisms for powers ranging from 0.3 to 3.0 W [16, 21]; meanwhile, Gonçalves et al. [6] showed 100 % bacterial elimination using 3.0 W (Table 4). In a similar manner to the $CO_2$ and GaAlAs diode lasers, the Nd:YAG laser demonstrated variable decontamination of microbial organisms with *E. faecalis* having higher resistance to irradiation than *P. gingivalis* [6].

## Discussion

This narrative review evaluated in vitro studies assessing the efficacy of lasers in the bacterial decontamination of dental implant surfaces.

Er:YAG lasers were the most consistent in inducing near-complete or complete bacterial decontamination over a wide range of powers (30–120 mJ/pulse, 10–30 Hz, SP mode). Both the $CO_2$ and GaAlAs diode lasers demonstrated near-complete bacterial decontamination capacities with 4–7 W at 20–80 Hz and 3 W, respectively, yet the number of studies showing complete bacterial elimination was equivocal. Additionally, microbes demonstrated different levels of resistance when irradiated with these lasers, indicating a potentially lower irradiation efficacy against a combined bacterial biofilm such as that involved in the aetiology of peri-implant diseases. There was no clear consensus in the analysed literature on the capacity of Nd:YAG laser in inducing complete decontamination of infected titanium specimens. An optimal irradiation protocol could not be reached for the evaluated lasers due to researchers employing differing test specimens, contamination methodologies, irradiation settings and outcome measures, which limited study comparability.

The level of decontamination varied for different titanium surfaces within the same trial where all other variables were controlled [6, 7, 11, 12, 18]. As a specific example, Quaranta et al. [18] reported decontamination values of 76.2 % for machined, 90.9 % for TPS and 98.3 % for sandblasted or acid-etched surfaces when using the Er:YAG laser with matching irradiation protocols. Thus, surface-specific factors rendered a particular surface easier or more challenging to decontaminate compared to another. Similarly, specimen geometry modified the level of decontamination. Root form is more supportive of bacterial growth due to its multiple crevices and threads. Elimination of bacterial species may occur less readily on a root-form specimen due to lowered laser access. Combining the root-form's higher contamination surface area and the lower laser access will lead to lower decontamination potential of a laser. Therefore, baseline specimen geometry and surface properties can affect the observed outcome, which limits the study comparability.

The comparability of the studies' outcomes has been limited by the variable contamination protocols. Given the varying levels of resistance of single microbial biofilm to a constant laser irradiation protocol [6, 8, 22], it is unfeasible to compare decontamination trials which used an indeterminate mixture of microbiological species from an intra-oral environment [9, 10, 13–15, 17, 23]. Incorporation of more resistant organisms in the infection protocol will lend a less favourable decontamination result to the laser used compared to a single susceptible microbial biofilm. Furthermore, the use of species that are not implicated in peri-implant disease, such as *Bacillus subtilis* [21], will skew the decontamination results. Studies allowed variable contamination time for biofilm formation following bacterial contamination, ranging from 10 min [20] to 10 days [23]. While a short duration may result in a less stable biofilm due to insufficient maturation time, a longer duration produces a degenerate biofilm secondary to noxious product formation and reduced nutrient availability. An appropriate length of contamination allows the formation of a stable biofilm, the protective nature of which decreases the efficacy of decontamination with laser irradiation. Incomplete or degenerate inconsistent biofilms provide a more favourable decontamination result but make it difficult to assess whether the lack of residual biofilm is due to the laser irradiation or due to the contamination protocol itself.

Exposure to the laser light energy gives phototoxic effects through inducing reactive oxygen species (ROS) production by the bacteria [24]. The amount of ROS production depends on the wavelength, hence the variable lasers' decontamination potential. Power settings dictate the actual rate of energy transfer to the surface per unit time and are directly

**Table 2** Carbon dioxide laser specifications used in in vitro studies evaluating the decontamination of titanium specimens with analysis mechanisms and key outcomes

| Study | Wavelength ($\lambda$) | Tip (μm) | Duration (s) | Mode | Power (fluence) | Decontamination potential |
|---|---|---|---|---|---|---|
| Kato et al. [8] | 10,600 nm | NR | 3–8 | NR | 15 J (122 J/cm$^2$)<br>20 J (163 J/cm$^2$) | CFU—bactericidal efficacy: |
| | | | | | 25 J (204 J/cm$^2$) | *S. sanguinis*: |
| | | | | | | 15 J: Machined (74.2 %) and sandblasted (80.2 %) |
| | | | | | 30 J (245 J/cm$^2$) | 35 and 40 J: 100 % machined and sandblasted surfaces |
| | | | | | 35 J (286 J/cm$^2$) | *P. gingivalis* (more sensitive): |
| | | | | | | At 15 J: machined (98.6 %) and sandblasted (98.7 %) |
| | | | | | 40 J (327 J/cm$^2$) | 30, 35, and 40 J: 100 % machined and sandblasted surfaces |
| Mouhyi et al. [9] | NR | NR | 10 | Continuous | 5 W | SEM: |
| | | | | | | Dry: surface contaminants were not reduced, burned tissue was still attached to the surface |
| | | | | | | Wet: surface contaminants were reduced, no carbonization/burning of the tissues occurred |
| Mouhyi et al. [10] | NR | NR | NR | Super pulsed | 7 W; 10 ms pulse width; 80 Hz | SEM: laser + citric acid + water rinsing + hydrogen peroxide + laser group—clean surface free of burned contaminants and residual bacteria |
| Shibli et al. [14] | 10,600 nm | NR | 40 | Continuous | 1.2 W (40 J) | SEM: the high laser energy burned rather than removed the contaminants |
| Hauser-Gerspach et al. [22] | 10,600 nm | Flexible hollow fibre | 10 | Continuous | 2 W (100 J/cm$^2$) | CFU: |
| | | | | | | *S. sanguinis*: |
| | | | | | | 2 W: 2 logs reduction—less effective kill |
| | | | | | | 4 W: >4 logs reduction—effectively killed |
| | | | | | 4 W (1,200 J/cm$^2$) | *P. gingivalis* (more sensitive): effectively killed regardless of power or surface type |
| Tosun et al. [20] | 10,600 nm | Hollow-wave guide fibre | 10 | Pulsed | 2 W, 20 Hz, 20 ms/pulse<br>4 W, 20 Hz, 10 ms/pulse | CFU—bacterial reduction:<br>2 and 4 W (20 Hz, 10 ms/pulse), 68 % |
| | | | | | 4 W, 20 Hz, 20 ms/pulse | 4 W (20 Hz, 20 ms/pulse), 97 % |
| | | | | | 6 W, 20 Hz, 20 ms/pulse | 6 W (20 Hz, 20 ms/pulse), 100 % |

**Table 3** Summary of GaAlAs diode laser specifications used in in vitro studies evaluating the decontamination of titanium specimens with analysis mechanisms and key outcomes

| Study | Wavelength ($\lambda$) | Tip (μm) | Duration (s) | Mode | Power | Decontamination potential |
|---|---|---|---|---|---|---|
| Haas et al. [7] | 905 nm | NR | 60 | Pulsed | 7.3 mW | Bacterial smears: laser therapy combined with toluidine blue dye (100 μg/ml)—no bacterial growth (*A. actinomycetemcomitans*, *P. gingivalis*, *P. intermedia*) post-irradiation in any surface (machined, TPS, HA, SA) |
| | | | | | | SEM: destroyed cell residues left post-irradiation |
| Kreisler et al. [12] | 809 nm | Optical fibre (600 μm) | 60 | Continuous | 0.5 W, 1.0 W, 1.5 W, 2.0 W, 2.5 W | CFU—bacterial reduction: |
| | | | | | | TPS: 45.0 % (0.5 W), 99.4 % (2.5 W) |
| | | | | | | SA: 57.6 % (0.5 W), 99.9 % (2.5 W) |
| | | | | | | HA: 98.2 % (2.0 W), 99.3 % (2.5 W)[a] |
| Sennhenn-Kirchner et al. [23] | 810 nm | Waveguide fibres (500 and 600 μm) | 20, 30 | Continuous pulsed | 1 W | CFU—bacterial reduction: |
| | | | | | | 810 nm, 99.66–99.98 % |
| | | | | | 1.5 W (20 Hz, 3 ms) | 980 nm cw, 99.38–99.57 % |
| | 980 nm | | | | | 980 nm P, 98.86 % |
| Sennhenn-Kirchner et al. [19] | 810 nm | Sapphire (600 μm) | 20 | Continuous | 1 W | Photometric XTT–formazan analysis of mitochondrial dehydrogenase activity: |
| | | | | | | Irradiated specimen, 0.02 |
| | | | | | | Non-irradiated specimen, 0.25[a] |
| | | | | | 353.7 W/cm$^2$ | SEM: GaAlAs diode only effective in direct contact mode |
| Hauser-Gerspach et al. [22] | 810 nm | Fibre (200 μm) | 10 | Continuous | 1.0 W (50 J/cm$^2$) | CFU: |
| | | | | | | *S. sanguinis*: |
| | | | | | | 2 W: 2 logs reduction—less effective kill |
| | | | | | | 4 W: >4 logs reduction—effectively killed |
| | | | | | | *P. gingivalis*: effectively killed regardless of power or surface type |
| Gonçalves et al. [6] | 980 nm | Optical fibre (300 μm) | 300 | Continuous | 2.5 W (1,143 J/cm$^2$) 3 W (1,371 J/cm$^2$) | CFU—bacterial reduction: |
| | | | | | | 2.5 W: *P. gingivalis*, 100 % (machined, sandblasted, SA); *E. faecalis*, 100 % (machined), 79 % (sandblasted), 50 % (SA) |
| | | | | | | 3.0 W: *P. gingivalis*, 100 % (machined, sandblasted, SA); *E. faecalis*, 100 % (machined, sandblasted, SA) |
| Tosun et al. [20] | 808 nm | R21B (320 μm) optic fibre | 10 | Continuous | 0.25 W, 0.5 W, 0.75 W, 1 W | CFU: |
| | | | | | | R21B (320 μm) optic fibre: 30 % (0.25 W), 97 % (1 W) |
| | | R24B handpiece | | | | R24-B handpiece: 28 % (0.25 W), 100 % (1 W) |

[a] Statistically significant

**Table 4** Nd:YAG laser specifications used in in vitro studies evaluating the decontamination of titanium specimens with analysis mechanisms and key outcomes

| Study | Laser (λ) | Tip (μm) | Duration (s) | Mode | Power | Decontamination potential |
|---|---|---|---|---|---|---|
| Block et al. [21] | 1,064 nm | Quartz fibre–optic handpiece | NR | Pulsed | 0.3 W, 10 pps<br>2.0 W, 20 pps<br>3.0 W, 30 pps | CFU: *B. subtilis* (9732) was recovered at all powers from both types of surfaces (plasma sprayed, HA coated) in both contact and non-contact modes (5 mm away) |
| Giannini et al. [16] | 1,064 nm | Glass fibre (400 μm) | 3–4 | Pulsed | 20 mJ, 50 Hz (1 W)<br>20 mJ, 70 Hz (1.4 W)<br>60 mJ,10 Hz (1.6 W)<br>100 mJ, 10 Hz (1 W) | LM and AFM: 20 mJ (50 and 70 Hz)—almost complete microbial ablation, destroyed bacterial residues with crater-like formation on the cell wall of the bacteria |
| Gonçalves et al. [6] | 1,064 nm | Optical fibre (300 μm) | 300 | Pulsed | 2.5 W (1,143 J/cm$^2$)<br>3 W (1,371 J/cm$^2$) | CFU—bacterial reduction:<br>2.5 W: *P. gingivalis*, 100 % (machined, sandblasted, SA); *E. faecalis*, 100 % (machined, sandblasted), 97 % (SA)<br>3.0 W: *P. gingivalis*, 100 % (machined, sandblasted, SA); *E faecalis*, 100 % (machined, sandblasted, SA) |

*pps* pulses per second, *LM* light microscopy, *AFM* atomic force microscopy

proportional to the level of ROS production and the level of expected bacterial kill. Various powers were employed in the included studies ranging from 30 to 200 mJ/pulse (5–30 Hz) in Er:YAG, from 1.2 to 7 W in $CO_2$, from 0.25 to 3 W in GaAlAs diode and from 0.3 to 3 W in Nd:YAG. Furthermore, power is determined by both the amount of energy per pulse as well as the frequency of pulses; alterations to these two key determinants can give a different true amount of energy experienced by the specimen per unit area. Studies did not always fully define the settings with respect to these two variables, hence limiting comparability.

Choices of tip type, distance between tip and specimen, irradiation time, mode and mechanism all influence the true amount of energy that the specimen receives which is different to the initial predetermined power. Schwarz et al. [15] demonstrated the reduction of the power of the Er:YAG laser from 100 mJ/pulse at 10 Hz as the base setting to 85 mJ/pulse at 10 Hz delivered to the titanium specimen using the cone-shaped glass fibre tip. Distances ranged from 0.5 mm [11, 13, 19, 22] to 30 mm [14]. As the distance between the tip and the irradiated specimen increases, the true energy experienced by the specimen will be reduced and the decontamination outcome will be less favourable. Likewise, the wide irradiation angle variation from 13° [13] to 90° [6, 22] gave variable decontamination because smaller irradiation angles give stronger waves. Irradiation times ranged from 3–4 s [16] to 336 s [15]; meanwhile, other studies did not report on this value [10, 21]. The time elapsed defines the total amount of energy delivered to the surface. The use of different mechanisms such as sweeping motion [13], apex-crown motions [18], manual scanning of disc surfaces [20], parallel irradiation in contact mode [15], successively enhanced concentric circles [11] and bilateral irradiation [19] will result in variable lengths of unit area exposure to the laser irradiation within a fixed time frame. Thus, the variable setting combinations make it difficult to correlate the reported power values to the actual decontamination outcomes and disable accurate comparisons between the studies.

Laser power output can be either continuous over the irradiation time or pulsed at a given frequency. The pulsed mode has been used in periodontal applications because the small volume of contaminated material and bacterial plaque on the implant surface can be evaporated if it is heated for a very short period of time [25]. However, a continuous mode supplies the energy gradually and allows for the heat to be absorbed into the bulk of the implant without attaining a sufficiently high temperature to evaporate the debris, resulting in lower surface decontamination [25]. The use of GaAlAs diode laser in a continuous wave mode resulted in equivocal evidence on the likelihood of complete bacterial decontamination.

Finally, different analytical techniques were used to measure the decontamination outcomes at different levels. While

light microscopy examines bacterial biofilm presence at the macroscopic level at relatively lower magnification, SEM carries out this analysis at a much higher magnification, which may entail more sensitivity and higher accuracy on reporting bacterial presence. However, these qualitative examinations provide no assessment of the viability of the residual bacterial plaque biofilm. CFU and bacterial smear tests examine the presence of viable species by assessing regrowth following an irradiation episode. However, variation has been observed in the carrying out of the CFU analysis and the different results can be the product of the utilisation of various dilutions. The analytical techniques measure various qualities at the macroscopic and microscopic level. This renders it substantially difficult to compare the different methods, the sensitivity of which can be questionable.

Energy transfer to a titanium surface to induce decontamination is associated with the development of surface colour changes and morphological damage. As the temperature surpasses the metallic melting and boiling thresholds of the surface, slip-line formation, ripple patterns, flat melting, crater-like formation and boiling occur [26]. It is unclear whether surface alterations will occur as a result of laser irradiation as variable results have been reported in the examined studies depending on the laser type and settings as well as the analytical mechanisms.

The comparability of the studies has been limited, and it was difficult to assess the extent to which the validity of the irradiation protocol conclusions has been affected by the wide variety in study design and outcome measures. This presents a clear need for devising a standardised irradiation protocol that is safe for in vivo use, is efficacious in bacterial decontamination and causes minimal surface alteration.

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**Conflict of interest** The authors declare that there are no conflicts of interest in this study.

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