

Jacek Matys, Ute Botzenhart*, Tomasz Gedrange and Marzena Dominiak

Thermodynamic effects after Diode and Er:YAG laser irradiation of grade IV and V titanium implants placed in bone – an *ex vivo* study. Preliminary report

DOI 10.1515/bmt-2015-0135

Received July 9, 2015; accepted February 17, 2016; online first March 17, 2016

Abstract: Many inserted implants are affected by peri-implantitis. The aim of our study was to evaluate increases in implant temperature, depending on the diameter and chemical composition of implants. In particular we measured the time it takes for the temperature of an implant to rise by 10°C and evaluated laser power settings required to prevent thermal injury when an implant surface is decontaminated during the treatment of peri-implantitis. The study analysed six implants placed in porcine ribs and divided into two groups according to their diameter and chemical composition (grade IV and grade V titanium). The implants were irradiated with Diode and Er:YAG lasers using different laser parameters. The temperature was measured with a K-type thermocouple. The temperature on the implant surface rose as the laser power increased and the implant diameter decreased. The time required to increase the temperature of an implant by 10°C was less than it was for titanium grade IV. The temperature gradient was below 10°C for all implants treated using a laser power up to 1 W. It is important to choose the correct laser parameters, depending on the chemical composition and diameter of the implant, so that decontamination of the implant surface is thorough, effective and safe.

Keywords: dental implants; Diode laser; Er:YAG laser; temperature; thermal conductivity; titanium alloy.

Introduction

Thanks to rapid advances in implantology over the last few decades, which has resulted in improvements in implant materials, designs and surface properties, achieving a tight connection between living bone and the implant surface, i.e. osseointegration, no longer poses a challenge. Clinical studies of 5-year implant survival rates show that 99.1% of implants in the mandible and 84.9% of implants in the maxilla become osseointegrated and represent a part of a fully functional prosthetic reconstruction [1, 8]. Implant osseointegration complication rates recorded in the literature vary considerably, with some researchers reporting 0% complications over a 5-year follow up period [56] while the highest rate in a 10-year follow up period being 29% [6]. However, numerous contemporary studies reveal that, despite correct implant osseointegration being achieved and proper oral hygiene being observed, many implants are still affected by peri-implantitis, which is one of the most common causes of implant loss [32, 45]. Recent studies indicated a peri-implantitis rate ranging from 11.3 to 47.1% after 8 years [22, 62]. Roos-Jansåker indicates that most inserted implants are affected by peri-implantitis after 9–14 years [44]. As a consequence, special attention should be paid to identifying effective and predictable methods of peri-implantitis treatment using modern medical technologies.

Peri-implantitis has a great deal in common with periodontitis. Nevertheless, there are some differences which require the use of a different and more complex technique to render the treatment effective [19]. Unlike a tooth, the surface of an implant is in direct contact with bone tissue. Around the implant there is neither periodontium nor cementum [30] and a constant physiological and homogeneous distribution of masticatory forces is prerequisite

***Corresponding author: Dr. Ute Botzenhart**, Department of Orthodontics, University Medical Center, Technische Universität Dresden, Fetscherstr. 74, Haus 28, D-01307 Dresden, Germany, Phone: 0049-351-4582718, Fax: 0049-351-4585318, E-mail: ute.botzenhart@uniklinikum-dresden.de

Jacek Matys: Private Dental Healthcare, Lipowa 18, 67-400 Wschowa, Poland

Tomasz Gedrange: Department of Orthodontics, University Medical Center, Technische Universität Dresden, 01307 Dresden, Germany

Marzena Dominiak: Dental Surgery Department Medical University, 50-368 Wrocław, Poland

for bone remodelling and preservation of the bone structure, especially in the critical part of the implant neck area, while overload can lead to continuous bone loss and should be avoided [40]. Furthermore the composition of the connective tissue is different with a different arrangement of fibres, fewer fibroblasts, a reduced blood supply and a change in immune defence compared to that of a natural tooth with a healthy periodontium [39]. A recent study conducted by Alligrini et al. revealed that an extension of crevicular epithelial cells could also be histologically demonstrated in the implant neck area [2]. Among other things, this makes the implant area more susceptible to periodontal disease and thus special treatment needs. Chemo-mechanical methods have lately been employed to debride implant surfaces [10, 25, 29, 41, 42, 48, 50, 58]. The complicated architecture of an implant makes establishing a decontamination protocol difficult. Therefore, traditional tools such as curettes, scalers and sickle probes are insufficient to ensure proper treatment of an implant surface contaminated with pathogens [59]. Another disadvantage of this protocol is the risk of damage occurring to the implant surface [21, 34, 61]. Diode and Er:YAG lasers could play a significant role in decontaminating an infected implant surface [46, 47]. However, particular attention should be paid to preventing overheating of the bone [18] when applying these devices during surgical procedures. Due to direct bone-implant-contact and the special composition of the soft tissue in the implant neck area, the blood flow in this area is reduced, which increases the risk of thermal injuries being transmitted by the implant to the bone tissue. Eriksson et al. found in a series of studies [12, 11] that increasing the temperature of bone tissue by 10°C for 60 s causes permanent changes in the bone structure. Therefore, a tissue temperature gradient (ΔT_a) below 10°C should be regarded as optimal and safe.

The implant temperature gradient depends on the differences in the physical and chemical properties of the titanium grades, in particular on thermal conductivity (TC), which is almost three times lower in grade V than in grade IV titanium [35] (Table 1).

Numerous reports have analysed the relationship between increases in implant surface temperature and the amount of laser energy applied [14, 15, 24, 28, 31, 37, 55, 60]. However, to the best of our knowledge no comparative study has been conducted on how much Diode and Er:YAG lasers at different energy settings increase implant temperature, taking into account the width and chemical composition of implants.

The aim of our study was to evaluate increases in implant temperature, taking into account the diameter and the titanium grade of implants. In particular, we

Table 1: The physical and chemical properties of titanium and its alloys according to the American Society for Testing and Materials (ASTM).

Grade of titanium	Tensile strength (MPa)	Modulus of elasticity (Gpa)	Density of (g/cm ³)	Elongation (%)	Thermal Conductivity (W/m-K)
CP I Ti	240	102	4.5	24	22.6
CP II Ti	345	102	4.5	20	22.6
CP III Ti	450	102	4.5	18	22.4
CP IV Ti	550	104	4.5	15	20.1
Ti6Al4V	930	113	4.4	10	6.9
Ti6Al4V ELI	860	113	4.4	10	6.9

measured the time it takes for the temperature of an implant to rise by 10°C and evaluated the laser power settings needed to prevent thermal injury when an implant surface is being decontaminated during the course of peri-implantitis treatment.

Materials and methods

The study was carried out on six implants that were 10 mm in length and divided into two groups according to their diameter (6.0 mm, 4.5 mm, 3.2 mm) and chemical composition (grade IV and grade V titanium). Group I included implants made of grade IV pure titanium (Dentium Co., Seoul, Korea) and group II included implants made of grade V titanium [AB Dental, Ashdod, Israel; Ti₆Al₄V ELI (extra low interstitial) alloy, composed of titanium, aluminium and vanadium] with one implant of each diameter.

The implants were placed in two ribs of a recently slaughtered pig intended for consumption and which had been obtained from a butcher. The distance between each implant was 2 cm. A total of three titanium grade V implants (AB Dental, Ashdod, Israel) were placed in the first rib while three titanium grade IV implants (Dentium Co., Seoul, Korea) were inserted in the second. Each implant had a different diameter. A hole (3 mm in diameter) was drilled in each bone at mid height with a trephine bur so as to simulate peri-implantitis.

The ribs were placed in a heated container that had been filled with water at a temperature of 37°C and kept there for 20 minutes so as to simulate the conditions of the oral environment. The temperature was monitored with a MCP (Medicare Clinical Products) Gold mercury thermometer (Medicare Products Inc., New Delhi, India). As a consequence, it was always possible to measure the temperature gradient starting from 37°C. The reaction to changes in implant temperature was measured with a calibrated digital Thermocouple Meter TM-902C thermometer (Zhangzhou Weihua Electronic Co., Fujian, China) by touching the internal thread of the implant neck with a probe. Due to the fact that laser irradiation was not possible with the ribs placed in water and to prevent a temperature fall, the implants were directly irradiated after the removal from the heated container. Every measurement was taken three times and the mean value was then subjected to statistical analysis (Figure 1). The temperature gradient for each sample was calculated as the difference between the



Figure 1: Monitoring and measurement of the reaction to changes in the temperature of the inserted implants.

initial temperature, immediately before laser irradiation, and the temperature rise immediately after laser irradiation. The measurement error was 0.5% using a K Thermocouple Probe temperature probe, type TP-02 (Zhangzhou Weihua Electronic Co., Fujian, China).

The lasers used in the research had the following parameters:

Er:YAG laser (LiteTouch®, Syneron Dental, Yokneam, Izrael):		
Power settings:	0.5 W	(50 mJ, 10 Hz, energy density per pulse: 6.37 J/cm ²)
	1 W	(100 mJ, 10 Hz, energy density per pulse: 12.74 J/cm ²)
	2 W	(200 mJ, 10 Hz, energy density per pulse: 25.48 J/cm ²)
	3 W	(300 mJ, 10 Hz, energy density per pulse: 38.21 J/cm ²)
	4 W	(400 mJ, 10 Hz, energy density per pulse: 50.96 J/cm ²)
Size of the tip:	1.0×17 mm	
Exposure time:	10 s, 20 s, 30 s	
Irradiation angle:	70°	
Non-contact mode at 1 mm distance		
Without cooling with water spray		
Diode laser (980 nm, Kavo®, Gentleray, Charlotte, NC, USA):		
Power settings:	0.5 W	(irradiance: 708 W/cm ²)
	1 W	(irradiance: 1415 W/cm ²)
	2 W	(irradiance: 2831 W/cm ²)
	3 W	(irradiance: 4246 W/cm ²)
	4 W	(irradiance: 5662 W/cm ²)
Spot diameter:	300 μm	
Exposure time:	10 s, 20 s, 30 s	
Irradiation angle:	70°	
Non-contact mode at 1 mm distance		
Continuous-mode		

Statistical analysis

The statistical analysis was based on ANOVA variance analysis and a t-test conducted using Statistica 10 software (StatSoft, Krakow, Poland). Values below $p=0.05$ were considered to be statistically significant.

Results

An analysis of temperature increases on implant surfaces in conjunction with increases in laser power revealed significant differences for the Diode laser after exposure times of 20 s and 30 s. When the other laser energy settings and exposure times were taken into account no significant different results could be found between the Diode and Er:YAG lasers (Figure 2).

Our findings show that following irradiation with the Diode and Er:YAG lasers, the implant temperature of grade IV implants increased much more rapidly than it did in the case of grade V implants. A significant implant temperature increase was observed following Diode and Er:YAG laser irradiation with 10 s and 30 s exposure times depending on the titanium grade used. The results after 20 s of irradiation indicated no significant implant temperature changes for either laser type (Figure 3).

Depending on the laser type used, no statistical significant differences in implant temperature rise were observed. However, the mean implant temperature increase after Er:YAG laser irradiation was lower than was the case when a Diode laser was used.

An analysis of implant temperature increase in relation to implant diameter revealed significant differences between both laser types in terms of a correlation between a rise in temperature and a decrease in implant diameter, with the exception of a 20 s exposure time. Furthermore, no significant differences were observed in the time required to heat up an implant by 10°C. However, grade IV titanium implants reached the target temperature in a shorter time than grade V titanium implants. The temperature of none of the grade V 6 mm diameter titanium implants rose by more than 10°C (Table 2) when applying the laser parameters used in this study.

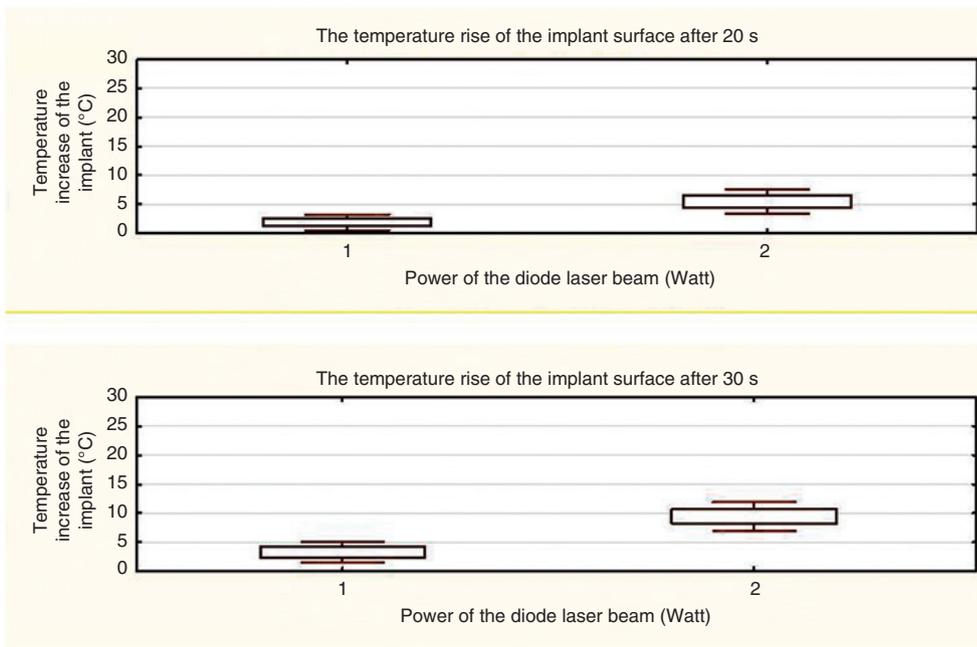


Figure 2: Temperature rise on implant surface along with increase in laser power (1 W, 2 W) using a Diode laser after 20 s and 30 s exposure time.

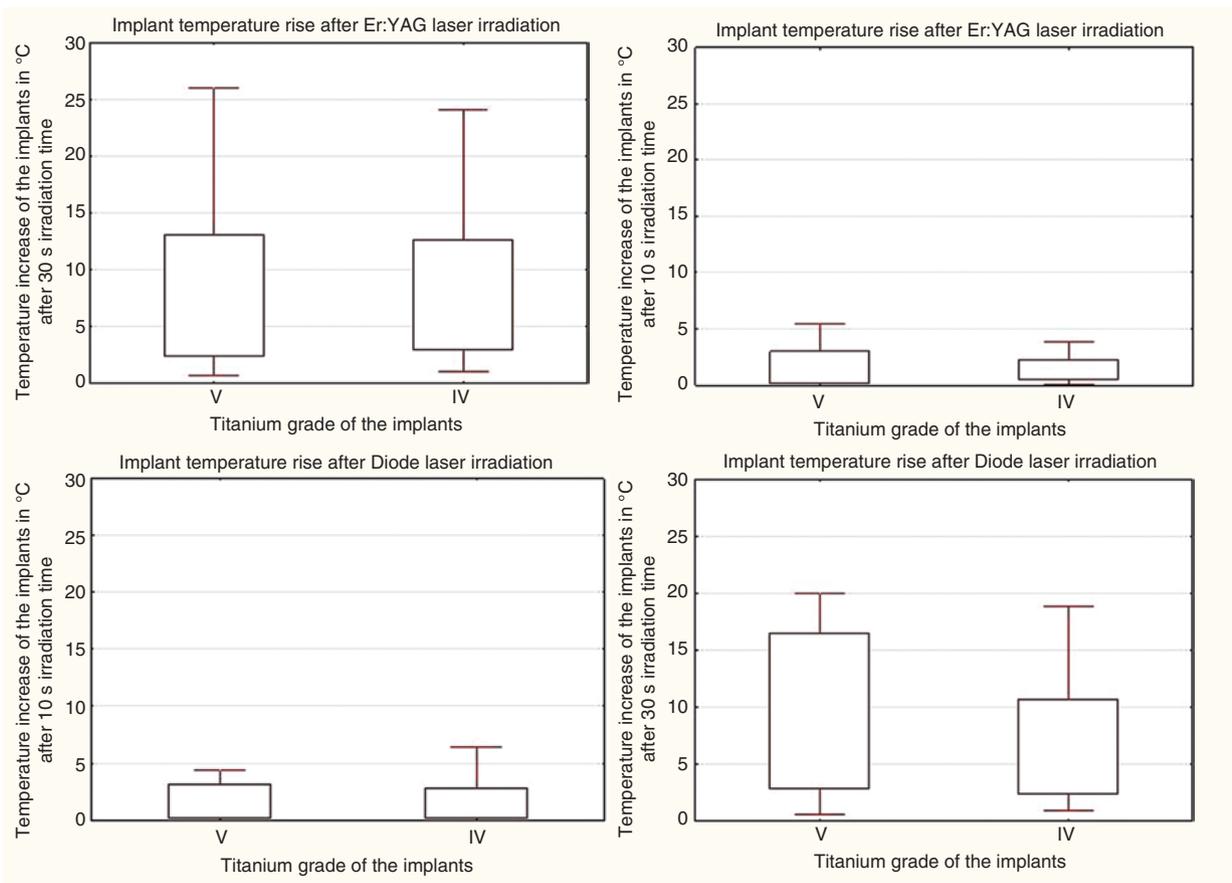


Figure 3: Implant temperature rise after Diode and Er:YAG laser irradiation depending on the titanium grade of the implants.

Table 2: The time and Power settings for Diode and Er:YAG lasers required to raise the temperature of an implant by 10°C.

	Diameter (mm)	Diode laser	Er:YAG laser
Grade IV titanium implants	3.2	17 s (3 W and 4 W), 29 s (2 W)	15 s (4 W), 24 s (3 W), 29 s (2 W)
	4.5	18 s (3 W and 4 W)	16 s (4 W), 26 s (3 W)
	6	18 s (3 W and 4 W)	18 s (4 W), 28 s (3 W)
Grade V titanium implants	3.2	18 s (3 W), 24 s (3 W)	18 s (4 W), 28 s (3 W)
	4.5	29 s (3 W)	28 s (4 W)
	6	–	–

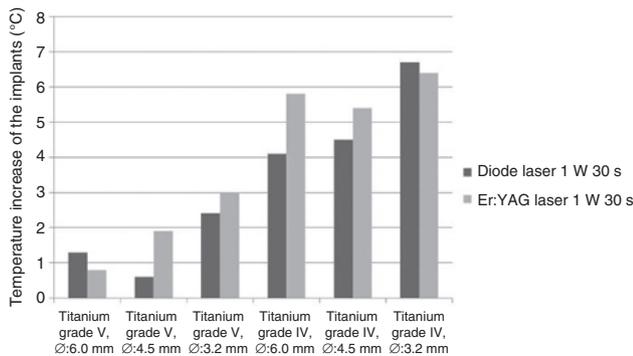


Figure 4: Effect of Diode and Er:YAG laser irradiation (Power setting: 1 W; 30 s exposure time) in raising the temperature of the implants, depending on the diameter and titanium grade, respectively.

The analysis showed that after 30 s irradiation time with an Er:YAG and Diode laser (power setting of 1 W), the temperature gradient was below 10°C in all the implants (Figure 4).

Discussion

To the best of our knowledge, no comparison has yet been made *ex-vivo* in the literature between the effects of Diode and Er:YAG laser irradiation in increasing the temperature of grade IV and V titanium implants. Nonetheless, the impact of lasers on implant temperature has already been analysed in relation to laser power [14, 15, 24, 28, 31, 37, 55, 60]. The main objective of this study was to determine effective and safe energy settings for Er:YAG and Diode lasers for most current implant sizes of implants made from pure titanium (grade IV) and titanium alloy (grade V; Ti₆Al₄V composed of 90% titanium, 6% aluminium, 4% vanadium, maximum 0.25% iron, maximum 0.2% oxygen) [7].

In their comparative analysis of increases in soft tissue temperature Mergio et al. stated that Er:YAG lasers resulted in a smaller rise in tissue temperature than Diode and CO₂-lasers [36]. Fornaini et al. also emphasised that an Er:YAG laser causes a smaller implant temperature increase than a Diode laser [14]. The results are similar to those obtained in our study. However, there was no statistically significant difference.

Taniguchi et al. defined the optimal Er:YAG laser parameters required to decontaminate an implant surface and not produce any changes in the microstructure of the implant. Those parameters were 30–50 mJ (30 Hz, 1.5 W; 10.6 mJ/cm²) [55]. In our study we tried to establish the safe parameters for Diode and Er:YAG lasers that do not cause a significant increase in the implant temperature (above 10°C), and found them to be 100 mJ (10 Hz, 1 W).

Studies using these laser parameters *in vitro* and *in vivo* reported a high decontamination potential [50, 48, 49, 53, 52, 13]. Several previous studies have confirmed the effectiveness of Er:YAG laser irradiation at 10 Hz [55]. For example 60 mJ/pulse, 10 Hz ensures reliable removal of bacterial cytotoxic components from implant surfaces *in vitro* without altering the surface morphology of microstructured surfaces [55] and Kreisler et al. reported a bactericidal reduction between 98.39% and 99.6% depending on the titanium surface properties using 60 mJ/pulse, 10 Hz [26]. Schwarz et al. evaluated the cell attachment on different titanium surfaces *in vitro* [48]. Supragingival plaque was built up for 24 h on acrylic splints with sand blasted and acid etched titanium discs. After Er:YAG laser irradiation using 100 mJ/pulse, 10 Hz (=12,7 J/cm²), SEM examination demonstrated nearly the same cell density per mm² as the control surface [48], indicating the high decontamination potential using these laser parameters. 100% bactericidal effects were consistently achieved even at 90 mJ/pulse, 10 Hz in short pulse mode [57]. Schwarz et al. compared the clinical effect of Er:YAG laser application using 100 mJ/pulse, 10 Hz with water cooling and that of mechanical debridement using plastic curettes and antiseptics (CHX 0.2%) for non-surgical treatment of peri-implantitis baseline, 3 and 6 month after therapy. Both therapies led to significant improvement of the investigated clinical parameters (PI=plaque index, BOP=bleeding on probing, PD=probing depth, GR=gingival recession, CAL=clinical attachment level) but a statistical significant greater reduction of BOP (52% improvement) compared to mechanical debridement (22% improvement) could be found for Er:YAG laser treatment after 6 month [50]. Nevertheless no reports about bacterial reduction and subgingival microflora after laser treatment had been carried out. In another study

by Schwarz et al. 94.2% clean implant surfaces and only 5.8% residual plaque biofilm could be found with the use of Er:YAG laser at 100 mJ/pulse, 10 Hz (=12.7 J/cm²) [49]. These laser parameters are in accordance with our study results recommended for safe thermal laser use. Sennhenn-Kirchner et al. reported a nearly complete removal of fungal cells with Er:YAG laser using the same laser parameters (100 mJ/pulse, 10 Hz) [53].

In an actual literature review, Kamel et al. critically evaluated studies assessing the *in vitro* efficiency of different lasers and settings in the bacterial decontamination of titanium implant surfaces. The potential of lasers to decontaminate titanium implant surfaces was confirmed by all studies included except by one using Nd:YAG laser [20]. Various powers for Er:YAG laser in the different studies ranged from 30–200 mJ/pulse, 5–30 Hz and for Diode laser the power settings ranged between 0.25 and 3 W [20]. Concerning decontamination potential of Diode and Er:YAG laser application in the non-surgical treatment of peri-implantitis no clear recommendations for safe and effective laser settings could be found [20].

In contrast to the Er:YAG laser, it seems that the Diode laser is not effective in removing calcified deposits [4, 38], hence, it is often recommended only as additional treatment tool to conventional scaling and debridement [51], but the potential temperature rise is also a point of interest in its clinical use. Fontana et al. investigated the bactericidal efficiency of the power intensity 0.4, 0.6, 0.8, 1 and 1.2 W of Diode laser in an experiment on rats [13]. Bacterial reduction was evident in all cycles irrespective of the power intensity and Romanos et al. reported that the Diode laser does not cause surface alterations of titanium even in a high energy level [43].

With wavelength of 810–980 nm and Power setting of 1 W a 98.86–99.98% bacterial reduction could be reached with Diode laser debridement [52]. Comparable results could also be confirmed by Tosun et al. at the same Power setting of 1 W [57]. On the other hand in a split mouth controlled clinical study about non-surgical treatment of peri-implantitis Arisan et al. could not find any additional positive effect of adjunctive Diode laser application (810 nm, 1 W, pulsed mode, 1 min, 1,5 J) on peri-implantitis healing after 1 and 6 month on rough acid etched and sand blasted implant surfaces compared to conventional mechanical scaling and debridement with plastic curettes [5]. Healing was assessed by periodontal indexes (baseline, after 1 month), microbiologic specimens (baseline, after 1 month) and radiographs (baseline, after 1 month) [5]. Using higher Power settings (2.5 W) a bacterial reduction of 99.4%–99.9% on the different titanium surfaces were reported [27]. For Diode laser, decontamination

capacity increased from 45% at 0.5 W to 99.9% at 2.5 W [27] and had nearly complete bacterial decontamination capacities with 3 W and 4–7 W at 20–80 Hz [20]. In our study the power settings of 3 and 4 W were only found to be safe in the case of titanium implants exceeding 4.5 mm diameter. Due to a different resistance of parodontopathogenic bacteria to laser light, there is a variable decontamination of microbial organisms, and implant surface morphology also plays a significant role in microbiota reduction [20]. For example *Enterococcus faecalis* and *Streptococcus sanguinis* were more resistant to Diode laser irradiation than *Porphyromonas gingivalis* [16, 17]. A 100% reduction of *P. gingivalis* could be reached on different implant surfaces irradiated with 2.5 W and 3 W without damaging any of the implant surfaces, whereas rough implants contaminated with *E. faecalis* and irrigated with 2.5 W were left partially contaminated (decontamination of 78.6% for sand blasted and 49.4% for acid etched implants) [16].

All these facts together makes variable decontamination protocols necessary. Therefore, it is the more important to know the temperature rise of the different implant types and materials which are safe for clinical use. Decontamination efficacy usually increases in a dose-dependent manner [20] and dependent on the wavelength of the used laser type. Due to this the anti-bacterial power needed for decontamination is different [16] so that probably even higher energy settings are required dependent on the species involved.

It should be noted that some authors compensate for the lower laser energy of the Er:YAG laser by using a higher frequency [55, 9]. However, in the authors' opinion compensating for lower laser energy with a higher impulse frequency is not the best solution, as it intensifies the thermal effect by reducing the time required for tissue cooling. This correlation has also been reported by Matsuyama et al. [33] and Aoki et al. [3] whereat the pulse repetition rate was the determining criterion for a temperature rise, increasing the risk of thermal damage of the titanium implant surface [54]. As a consequence, increased laser power at a lower frequency ensures reduced thermal effects. On the other hand, in the case of continuous-wave lasers, i.e. CO₂-lasers, a lower power level is recommended for precise cutting.

Similarly to research conducted by Kreisler et al. [24], Wooten et al. [60] and Lambrecht et al. [28], we observed that implant temperature increased along with laser power.

In their *in vitro* study on implants placed in vinyl polysiloxen (VPS), Geminiani et al. stated that a temperature rise of more than 10°C (ΔT_a) could be recorded 10 s after Diode laser application (980 nm and 810 nm)

using a power setting of 2 W [15]. In our study a temperature rise of more than 10°C could only be observed in the case of grade IV titanium implants (smallest diameter; 3.2 mm) after 29 s of irradiation using a Diode laser. However, the implants had been placed in the ribs of a recently slaughtered pig. Therefore, the bone tissue in direct contact with the implants helped slow down the rise in implant temperature. Lejla et al. reported that in the case of implants inserted in bovine ribs, an increase in temperature could be observed after 18 s of irradiation with an Er:YAG laser [31].

We assumed that a maximum implant surface temperature rise of 10°C would be optimal and safe for bone tissue. The results for both laser types showed that the temperature did not rise by more than 10°C for either of the analysed implants with a laser setting of 1 W and an exposure time of 30 s. Such outcomes are in accordance with a study conducted by Monzavi et al., who reported that implants irradiated with an Er:YAG laser (power setting of 100 mJ; 10 Hz; 1 W) rose in temperature by 4.30°C on average after 60 s exposure time [37]. Similar results were reported by Kreisler et al., who observed a temperature rise of below 10°C after Er:YAG laser irradiation and with Power settings of 60–120 mJ (10 Hz; 120 s irradiation time) [23]. However, the authors did not differentiate between the analysed implants in terms of their composition and physical properties, in particular their TC, which in the case of pure titanium is three times higher than it is for titanium alloys.

The higher TC of grade IV titanium implants may lead to a considerable increase in implant temperature during irradiation, which, in turn, may result in the bone tissue overheating. Due to better decontamination of the infected implant surface, therefore, higher power settings (3 W–4 W) for Er:YAG and Diode lasers may particularly be considered for grade V titanium implants exceeding 4.5 mm diameter. Further studies should be conducted to assess the impact of lasers on the surface structure and the continuity of the titanium oxide layer covering the implant surfaces, as well as to analyse increases in implant temperature *in vivo*.

Conclusion

An excessive rise in implant temperature, induced by a laser light, may result in irreversible changes in the bone structure due to overheating. Implants composed of grade IV titanium heat up much faster than grade V titanium implants composed of titanium, aluminium and

vanadium alloy. Prior to the treatment of peri-implantitis, correct laser parameters should be chosen, depending on the chemical composition (titanium grade) and the diameter of the implant, as well as the laser type, so that decontamination of the implant surface is thorough, effective and safe. It is generally recommended that the settings for Diode and Er:YAG laser application should not exceed 2 W and 30 s exposure time. However, in our study, in which we analysed grade V titanium implants exceeding 4.5 mm in diameter, laser power settings of 3 W or 4 W were also within the safety limits.

References

- [1] Albrektsson T, Dahl E, Enbom L, et al. Osseointegrated oral implants. A Swedish multicenter study of 8139 consecutively inserted Nobelpharma implants. *J Periodontol* 1988; 59: 287–296.
- [2] Allegrini S, Jr., Allegrini MR, Yoshimoto M, et al. Soft tissue integration in the neck area of titanium implants—an animal trial. *J Physiol Pharmacol* 2008; 59(Suppl 5): 117–132.
- [3] Aoki A, Miura M, Akiyama F, et al. In vitro evaluation of Er:YAG laser scaling of subgingival calculus in comparison with ultrasonic scaling. *J Periodontol Res* 2000; 35: 266–277.
- [4] Aoki A, Sasaki KM, Watanabe H, Ishikawa I. Lasers in nonsurgical periodontal therapy. *Periodontol* 2000 2004; 36: 59–97.
- [5] Arisan V, Karabuda ZC, Arici SV, Topcuoglu N, Kulekci G. A randomized clinical trial of an adjunct diode laser application for the nonsurgical treatment of peri-implantitis. *Photomed Laser Surg* 2015; 33: 547–554.
- [6] Binahmed A, Stoykewych A, Hussain A, Love B, Pruthi V. Long-term follow-up of hydroxyapatite-coated dental implants—a clinical trial. *Int J Oral Maxillofac Implants* 2007; 22: 963–968.
- [7] Boyer R, Welsch G, Collings EW. *Materials Properties Handbook, Titanium Alloys*, Materials Park, OH. ASM International 1994: 176.
- [8] Buser D, Mericske-Stern R, Dula K, Lang NP. Clinical experience with one-stage, non-submerged dental implants. *Adv Dent Res* 1999; 13: 153–161.
- [9] Chen CK, Chang NJ, Ke JH, Fu E, Lan WH. Er:YAG laser application for removal of keratosis using topical anesthesia. *J Dent Sci* 2013; 8: 196–199.
- [10] Claffey N, Clarke E, Polyzois I, Renvert S. Surgical treatment of peri-implantitis. *J Clin Periodontol* 2008; 35(8 Suppl): 316–332.
- [11] Eriksson AR, Albrektsson T, Magnusson B. Assessment of bone viability after heat trauma. A histological, histochemical and vital microscopic study in the rabbit. *Scand J Plastic Recon* 1984; 18: 261–268.
- [12] Eriksson AR, Albrektsson T. Temperature threshold levels for heat-induced bone tissue injury: a vital-microscopic study in the rabbit. *J Prosthet Dent* 1983; 50: 101–107.
- [13] Fontana CR, Kurachi C, Mendonca CR, Bagnato VS. Microbial reduction in periodontal pockets under exposition of a medium power diode laser: an experimental study in rats. *Lasers Surg Med* 2004; 35: 263–268.

- [14] Fornaini C, Merigo E, Vescovi P, et al. Different laser wavelengths comparison in the second-stage implant surgery: an ex vivo study. *Lasers Med Sci* 2015; 30: 1631–9.
- [15] Geminiani A, Caton JG, Romanos GE. Temperature change during non-contact diode laser irradiation of implant surfaces. *Lasers Med Sci* 2012; 27: 339–342.
- [16] Goncalves F, Zanetti AL, Zanetti RV, et al. Effectiveness of 980-nm diode and 1064-nm extra-long-pulse neodymium-doped yttrium aluminum garnet lasers in implant disinfection. *Photomed Laser Surg* 2010; 28: 273–280.
- [17] Hauser-Gerspach I, Stubinger S, Meyer J. Bactericidal effects of different laser systems on bacteria adhered to dental implant surfaces: an in vitro study comparing zirconia with titanium. *Clin Oral Implants Res* 2010; 21: 277–283.
- [18] Heinemann F, Hasan I, Kunert-Keil C, et al. Experimental and histological investigations of the bone using two different oscillating osteotomy techniques compared with conventional rotary osteotomy. *Anna Anat* 2012; 194: 165–170.
- [19] Heitz-Mayfield LJ. Peri-implant diseases: diagnosis and risk indicators. *J Clin Periodontol* 2008; 35(8 Suppl): 292–304.
- [20] Kamel MS, Khosa A, Tawse-Smith A, Leichter J. The use of laser therapy for dental implant surface decontamination: a narrative review of in vitro studies. *Lasers Med Sci* 2014; 29: 1977–1985.
- [21] Koka S, Han J, Razzoog ME, Bloem TJ. The effects of two air-powder abrasive prophylaxis systems on the surface of machined titanium: a pilot study. *Implant Dent* 1992; 1: 259–265.
- [22] Koldslund OC, Scheie AA, Aass AM. Prevalence of peri-implantitis related to severity of the disease with different degrees of bone loss. *J Periodontol* 2010; 81: 231–238.
- [23] Kreisler M, Al Haj H, d'Hoedt B. Temperature changes at the implant-bone interface during simulated surface decontamination with an Er:YAG laser. *Int J Prosthodont* 2002; 15: 582–587.
- [24] Kreisler M, Al Haj H, D'Hoedt B. Temperature changes induced by 809-nm GaAlAs laser at the implant-bone interface during simulated surface decontamination. *Clin Oral Implants Res* 2003; 14: 91–96.
- [25] Kreisler M, Kohnen W, Christoffers AB, et al. In vitro evaluation of the biocompatibility of contaminated implant surfaces treated with an Er: YAG laser and an air powder system. *Clin Oral Implants Res* 2005; 16: 36–43.
- [26] Kreisler M, Kohnen W, Marinello C, et al. Bactericidal effect of the Er:YAG laser on dental implant surfaces: an in vitro study. *J Periodontol* 2002; 73: 1292–1298.
- [27] Kreisler M, Kohnen W, Marinello C, et al. Antimicrobial efficacy of semiconductor laser irradiation on implant surfaces. *Int J Oral Maxillofac Implants* 2003; 18: 706–711.
- [28] Lambrecht JT, Nyffeler T, Linder M. Thermal conduction of titanium implants under CO₂ laser irradiation in vitro. *Annal Maxillofac Surg* 2012; 2: 12–16.
- [29] Lang NP, Wilson TG, Corbet EF. Biological complications with dental implants: their prevention, diagnosis and treatment. *Clin Oral Implants Res* 2000; 11(Suppl 1): 146–155.
- [30] Laskus-Perendyk A, Perendyk J. Uwarunkowania anatomiczne- czynnościowe i leczenie zapaleń okołowszczepowych. *Implantatprotetyka* 2002; 2: 7–13.
- [31] Leja C, Geminiani A, Caton J, Romanos GE. Thermodynamic effects of laser irradiation of implants placed in bone: an in vitro study. *Lasers Med Sci* 2013; 28: 1435–1440.
- [32] Lindhe J, Meyle J, Group DoEWoP. Peri-implant diseases. Consensus Report of the Sixth European Workshop on Periodontology. *J Clin Periodontol* 2008; 35(8 Suppl): 282–285.
- [33] Matsuyama T, Aoki A, Oda S, Yoneyama T, Ishikawa I. Effects of the Er:YAG laser irradiation on titanium implant materials and contaminated implant abutment surfaces. *J Clin Laser Med Surg* 2003; 21: 7–17.
- [34] McCollum J, O'Neal RB, Brennan WA, Van Dyke TE, Horner JA. The effect of titanium implant abutment surface irregularities on plaque accumulation in vivo. *J Periodontol* 1992; 63: 802–805.
- [35] McCracken M. Dental implant materials: commercially pure titanium and titanium alloys. *J Prosthodont* 1999; 8: 40–43.
- [36] Merigo E, Clini F, Fornaini C, et al. Laser-assisted surgery with different wavelengths: a preliminary ex vivo study on thermal increase and histological evaluation. *Lasers Med Sci* 2013; 28: 497–504.
- [37] Monzavi A, Shahabi S, Fekrazad R, Behruzi R, Chiniforush N. Implant surface temperature changes during Er:YAG laser irradiation with different cooling systems. *J Dent (Tehran)* 2014; 11: 210–215.
- [38] Moritz A, Schoop U, Goharkhay K, et al. Treatment of periodontal pockets with a diode laser. *Lasers Surgery Med* 1998; 22: 302–311.
- [39] Pietruski JK, Pietruski MD, Dzięcioł J, Stokowska W, Pattarelli GM. Morfologia dziąsła w procesie osteointegracji implantów. *Czas Stomatol* 2001; 54: 372–376.
- [40] Rahimi A, Bourauel C, Jager A, Gedrange T, Heinemann F. Load transfer by fine threading the implant neck—a FEM study. *J Physiol Pharmacol* 2009; 60(Suppl 8): 107–112.
- [41] Renvert S, Polyzois I, Maguire R. Re-osseointegration on previously contaminated surfaces: a systematic review. *Clin Oral Implants Res* 2009; 20(Suppl 4): 216–227.
- [42] Renvert S, Roos-Jansaker AM, Claffey N. Non-surgical treatment of peri-implant mucositis and peri-implantitis: a literature review. *J Clin Periodontol* 2008; 35(8 Suppl): 305–315.
- [43] Romanos GE, Everts H, Nentwig GH. Effects of diode and Nd:YAG laser irradiation on titanium discs: a scanning electron microscope examination. *J Periodontol* 2000; 71: 810–815.
- [44] Roos-Jansaker AM. Long time follow up of implant therapy and treatment of peri-implantitis. *Swed Dent J Suppl* 2007: 7–66.
- [45] Sakka S, Baroudi K, Nassani MZ. Factors associated with early and late failure of dental implants. *J Invest Clin Dent* 2012; 3: 258–261.
- [46] Schwarz F, Bieling K, Nuesry E, Sculean A, Becker J. Clinical and histological healing pattern of peri-implantitis lesions following non-surgical treatment with an Er:YAG laser. *Lasers Surg Med* 2006; 38: 663–671.
- [47] Schwarz F, Jepsen S, Herten M, Sager M, Rothamel D, Becker J. Influence of different treatment approaches on non-submerged and submerged healing of ligature induced peri-implantitis lesions: an experimental study in dogs. *J Clin Periodontol* 2006; 33: 584–595.
- [48] Schwarz F, Rothamel D, Sculean A, Georg T, Scherbaum W, Becker J. Effects of an Er:YAG laser and the Vector ultrasonic system on the biocompatibility of titanium implants in cultures of human osteoblast-like cells. *Clin Oral Implants Res* 2003; 14: 784–792.
- [49] Schwarz F, Sculean A, Romanos G, et al. Influence of different treatment approaches on the removal of early plaque biofilms

- and the viability of SAOS2 osteoblasts grown on titanium implants. *Clin Oral Investig* 2005; 9: 111–117.
- [50] Schwarz F, Sculean A, Rothamel D, Schwenzer K, Georg T, Becker J. Clinical evaluation of an Er:YAG laser for nonsurgical treatment of peri-implantitis: a pilot study. *Clin Oral Implants Res* 2005; 16: 44–52.
- [51] Sculean A, Schwarz F, Becker J. [Anti-infective therapy with an Er:YAG laser: influence on peri-implant healing](#). *Expert Rev Med Devices* 2005; 2: 267–276.
- [52] Sennhenn-Kirchner S, Klaue S, Wolff N, Mergeryan H, Borg von Zepelin M, Jacobs HG. Decontamination of rough titanium surfaces with diode lasers: microbiological findings on in vivo grown biofilms. *Clin Oral Implants Res* 2007; 18: 126–132.
- [53] Sennhenn-Kirchner S, Schwarz P, Schliephake H, Konietzschke F, Brunner E, Borg-von Zepelin M. Decontamination efficacy of erbium:yttrium-aluminium-garnet and diode laser light on oral *Candida albicans* isolates of a 5-day in vitro biofilm model. *Lasers Med Sci* 2009; 24: 313–320.
- [54] Takasaki AA, Aoki A, Mizutani K, Kikuchi S, Oda S, Ishikawa I. [Er:YAG laser therapy for peri-implant infection: a histological study](#). *Lasers Med Sci* 2007; 22: 143–157.
- [55] Taniguchi Y, Aoki A, Mizutani K, et al. [Optimal Er:YAG laser irradiation parameters for debridement of microstructured fixture surfaces of titanium dental implants](#). *Lasers Med Sci* 2013; 28: 1057–1068.
- [56] Tinsley D, Watson CJ, Russell JL. A comparison of hydroxylapatite coated implant retained fixed and removable mandibular prostheses over 4 to 6 years. *Clin Oral Implants Res* 2001; 12: 159–166.
- [57] Tosun E, Tasar F, Strauss R, Kivanc DG, Ungor C. Comparative evaluation of antimicrobial effects of Er:YAG, diode, and CO(2) lasers on titanium discs: an experimental study. *J Oral Maxillofac Surg* 2012; 70: 1064–1069.
- [58] Trejo PM, Bonaventura G, Weng D, Caffesse RG, Bragger U, Lang NP. Effect of mechanical and antiseptic therapy on peri-implant mucositis: an experimental study in monkeys. *Clin Oral Implants Res* 2006; 17: 294–304.
- [59] Wilson V. An insight into peri-implantitis: a systematic literature review. *Prim Dent J* 2013; 2: 69–73.
- [60] Wooten CA, Sullivan SM, Surpure S. Heat generation by super-pulsed CO2 lasers on plasma-sprayed titanium implants: an in vitro study. *Oral surgery, oral medicine, oral pathology, oral radiology, and endodontics* 1999; 88: 544–548.
- [61] Zablotsky MH, Wittrig EE, Diedrich DL, Layman DL, Meffert RM. Fibroblastic growth and attachment on hydroxyapatite-coated titanium surfaces following the use of various detoxification modalities. Part II: Contaminated hydroxyapatite. *Implant Dent* 1992; 1: 195–202.
- [62] Zitzmann NU, Berglundh T. Definition and prevalence of peri-implant diseases. *J Clin Periodontol* 2008; 35(8 Suppl): 286–291.