

## RESEARCH ARTICLE

# Thermographic Effects of 445 nm Laser in Periodontal and Periapical Areas Ex Vivo

Grace Kang<sup>1,†</sup>, Jamie Wu<sup>1,†</sup>, Ghaedsharafi Yasamin<sup>1</sup>, Jiayue Han<sup>1</sup>, Thomas Manders<sup>1</sup>, Rafael Delgado-Ruiz<sup>2</sup> and Georgios E. Romanos<sup>1,\*</sup>

<sup>1</sup>Department of Periodontics and Endodontics, Stony Brook University, USA

<sup>2</sup>Department of Prosthodontics and Digital Technology, Stony Brook University, USA

**Abstract:** The objective of the study was to evaluate heat transfer within periodontal and periapical tissues when exposed to a 445 nm diode laser operating in continuous-wave (c.w.) versus pulsed mode. Mandibular bovine anterior teeth were endodontically prepared, and posterior teeth were used for laser-assisted periodontal therapy. A 445 nm diode laser was irradiated on root canals (120  $\mu$ m glass fiber) and periodontal pockets (320  $\mu$ m glass fiber) for 30 s ( $n = 20$ ) at 2W in c.w. and pulsed modes (15 Hz, 50% duty cycle) using non-initiated tips. The maximum temperature changes (in  $^{\circ}$ C) and heat transfer in height (vertical surface temperature distribution) and width (lateral heat transfer) were captured using a thermographic infrared camera. Mean periodontal heat temperature changes (in  $^{\circ}$ C) were  $36.53 \pm 10.32$  (c.w.) and  $22.32 \pm 8.46$  (pulsed). In the periapical areas, the temperature changes were  $11.65 \pm 4.46$  and  $7.74 \pm 2.40$ , respectively. In the periodontal tissues, lateral heat transfer was  $6.13 \pm 0.85$  mm in c.w. mode and  $6.94 \pm 1.03$  mm in pulsed mode. In the periapical areas, lateral heat transfer was  $4.11 \pm 0.75$  mm in c.w. mode and  $3.59 \pm 0.32$  mm in pulsed mode. The vertical surface temperature distribution in periodontal tissues showed similar patterns to periapical areas with minimal difference in both modes. Within the limitations of this study, a 445 nm diode laser caused a higher temperature change in continuous waves and produced greater lateral heat transfer than vertical spread in periodontal and endodontic applications.

**Keywords:** 445 nm diode laser, continuous-wave mode, infrared thermography, lateral heat transfer, non-initiated fiber tip

## 1. Introduction

Lasers are valuable tools in periodontics, endodontics, oral surgery, and implantology. They can cut, coagulate, decontaminate, and photo-bio modulate tissues [1–6]. The target tissues' absorption characteristics determine the type of laser to use, and the way each wavelength is absorbed by those tissues determines the laser's clinical impact [1]. These wavelength-dependent interactions explain why specific laser systems are preferred for particular procedures. Widely used lasers, such as diode lasers (810–980 nm), have been employed in surgical excisions including gingivectomies, frenectomies, and second-stage implant surgeries because they are absorbed by hemoglobin and melanin [2, 3]. Another commonly used device is the CO<sub>2</sub> laser, which demonstrates superficial interaction due to its high absorption in water, while the Er:YAG laser is often used in periodontics for removing subgingival calculus [4]. A relatively new diode laser operating in the visible blue spectrum at 445 nm has been introduced in dentistry, which is highly absorbed by hemoglobin and melanin. This wavelength demonstrates enhanced coagulation, efficient ablation, and notable antimicrobial effects due to its photochemical action

on bacterial cell membranes [5, 6]. Comparison of the biophysical properties of laser radiation between diode lasers with wavelengths of 445 nm and 810–980 nm shows that the absorption constant for the 445 nm wavelength has a significantly higher level of absorption in melanin and hemoglobin compared to 810–980 nm diode lasers. Furthermore, while absorption in water is lower for 445 nm than 810–980 nm diode lasers, the absorption in collagen increases significantly in the blue light spectrum. In addition, scattering in the blue light spectrum also increases [5].

## 2. Literature Review

Kim et al. [7] conducted a study on the effect of 625 nm, 525 nm, and 425 nm light-emitting diodes on removing the *Porphyromonas gingivalis*, *Staphylococcus aureus*, and *Escherichia coli*. The result showed that wavelengths of 425 and 525 nm had bactericidal effects, which further solidifies the blue light diode antimicrobial effect. Further expanding from Kim et al.'s study [7], researchers have found that a blue light diode laser with a wavelength of 445 nm has bactericidal effects on root canal dentin *Enterococcus faecalis*, cavity disinfection, and decontamination for titanium implant bodies [8–10]. Although those studies are conducted under the same wavelength, other diode emission parameters, such as power, emission mode, and the surface of applications, are important to consider.

\*Corresponding author: Georgios E. Romanos, Department of Periodontics and Endodontics, Stony Brook University, USA. Email: [georgios.romanos@stonybrookmedicine.edu](mailto:georgios.romanos@stonybrookmedicine.edu)

† Co-first author

Different emission parameters could have an impact on the tissue surface damage, especially thermal damage on diode lasers. To quantify the thermal damage, heat generated by a laser could be measured by the temperature change of the tissue pre- to post-irradiation [11]. Foundational studies by Eriksson et al. [12–14] established that temperatures above 47 °C sustained for 1 min induce bone thermal necrosis. Excessive heat generation raises concerns not only about soft and hard tissue damage but also implant surface damage, as recently demonstrated in Pergoliti et al.'s in vitro study [15]. Consequently, it is important to investigate how different diode laser emission parameters affect the temperature behavior in soft and hard tissues. For the power parameter in a diode laser, Gutiérrez-Corrales et al. [16] found that the area of the thermal damage is correlated to the power applied in the periodontal pocket. Pulse frequency also influences temperature changes during soft-tissue laser surgery. In vitro studies have shown that continuous-wave (c.w.) operation produces more tissue damage than pulsed mode, largely because the intermittent on/off cycle of pulsed delivery allows for cooling [17]. However, when low pulse frequencies are used (15 Hz), the pulsation prevents the heat from dissipating, allowing tissues to experience continuous heating over a biologically relevant timescale. In addition, research on bovine tongue tissue demonstrated that the 445 nm diode laser generates greater temperature increases when used with initiated tips compared to non-initiated tips [18].

Despite growing interest in the thermal effects of diode lasers, there remains a lack of studies examining the thermogenic behavior of 445 nm diode lasers in periodontal and periapical tissues under c.w. and pulsed modes. Accordingly, the objective of this study was to evaluate heat transfer from the anterior tooth canal to the periodontal tissues and from the periodontal tissues adjacent to molars to the surrounding structures, when exposed to a 445 nm blue diode laser operating in c.w. and pulsed modes.

### 3. Research Methodology

#### 3.1. Sample preparation

One mandibular bovine jaw with all the teeth and complete periodontal tissues was sourced from a local market with daily direct access to slaughtered cows. To assess the effects of the 445 nm laser in periapical and periodontal areas, heat transfer from the tooth canal to the periodontal tissues was evaluated in anterior teeth, while heat transfer from the periodontal tissues to the surrounding structures was evaluated in four posterior teeth. The eight mandibular bovine anterior teeth were endodontically prepared after instrumentation up to #70/.04 #70/.04 ProFile<sup>AE</sup>-rotary files, and the posterior teeth were used for laser-assisted periodontal therapy.

#### 3.2. Laser irradiation protocol

A 445 nm diode laser (SiroBlue, Sirona, Bensheim, Germany) was used in two modes: c.w. and pulsed mode (15 Hz, 50% duty cycle). For periapical (canal treatment) models, the root canal was irradiated with a 120 µm glass fiber non-initiated tip for 30 s, while periodontal pockets stimulated for periodontal models were irradiated with a 320 µm glass fiber non-initiated tip for 30 s. For both groups, the irradiation power was set at a 2-watt power level, achieving a power intensity of 2488 W/cm<sup>2</sup>, and each

experimental group consisted of 20 specimens ( $n = 20$ ). For each mode, 20 anterior root canals to the apex level and 20 posterior periodontal pockets (in molars) were irradiated to the depth of the pocket without water irrigation, resulting in four experimental groups adding to a total of 80 trials. The fiber tips were re-cleaved between each trial to ensure consistent power output and reproducibility. If damage was observed, the tip was replaced by a new one. The used irradiation protocol was based on conventional protocols for endodontic laser therapy or periodontal laser therapy.

#### 3.3. Thermographic recording

The maximum temperature changes (in °C) and heat transfer in height (vertical surface temperature distribution) and width (lateral heat transfer) were recorded using a thermographic infrared camera (8640P Series, ICI Infrared cameras, Inc., Beaumont, TX, USA), which was placed perpendicular to the beam direction at a distance of 50 cm at room temperature. This ensures geometric consistency and minimizes angle-dependent measurement errors. The camera was factory-calibrated with a sensitivity of < 0.04 °C.

During the irradiation period, heat transfer in the periapical and periodontal regions was measured and calculated (in mm) using IR FlashPro Software<sup>®</sup> (Infrared Cameras Inc., USA). In this study, two primary metrics will be used to evaluate the thermal behavior: lateral heat transfer and vertical surface temperature distribution. Lateral heat transfers measure the spread of heat to adjacent healthy tissues, indicating safety, while vertical surface temperature distribution measures the amount of energy reached within the target area, indicating efficacy of the laser. To minimize the environmental interference or calibration offsets, Temperature variation ( $\Delta T$ ) was determined by the difference between the baseline temperature (ambient room conditions) and the highest temperature recorded. Both lateral heat transfer and penetration depth were quantified to discern thermal energy dispersion between the c.w. and pulsed laser models. Measurements for the thermal spread were taken from the on-screen digital scale. To account for any scaling discrepancies and to convert digital dimensions into precise soft-tissue dimensions, the mathematical equation  $A_1/S_1 = A_2/S_2$  is used, where  $A$  represents the actual tissue dimension (mm) and  $S$  represents the corresponding on-screen measurement (mm). Length and breadth of the area impacted by thermal energy were measured approximately two-thirds of the radius from the center of heat loss (the highest temperature point). For terminology clarification, “lateral heat transfer” (irradiation length) is defined as the maximum thermal expansion horizontally (mm), highlighting potential collateral thermal damage. Clinically, vertical surface temperature distribution is defined as the maximum thermal propagation along the root axis.

#### 3.4. Statistical analysis

Descriptive statistics were performed, presenting mean values and standard deviations. Comparative statistics between c.w. and pulsed modes were calculated using the paired  $t$ -test at the 5% statistical significance level. In addition, Cohen's  $d$  (effect size) was calculated to assess the magnitude of differences between groups. All specimens were derived from a single mandibular source to control for inter-subject anatomical variation, though this limits the biological generalizability of the findings.

### 4. Results

Thermographic analysis displayed different patterns of temperature rise and heat distribution between periodontal and periapical tissues when irradiated with a 445 nm diode laser. In the *periapical areas*, the temperature changes ( $\Delta T$ ) were lower, with mean values of  $11.65 \pm 4.46$  °C in c.w. mode and  $7.74 \pm 2.40$  °C in pulsed mode. In *periodontal tissues*, the mean temperature was  $36.53 \pm 10.32$  °C in c.w. mode and  $22.32 \pm 8.46$  °C in pulsed mode.

Heat distribution between periapical and periodontal regions showed different results. In the periapical areas, lateral heat transfer was  $4.11 \pm 0.75$  mm in c.w. mode and  $3.59 \pm 0.32$  in pulsed mode ( $p = 0.021$ ) (Figures 1 and 2).

Vertical surface temperature distribution was similar in both modes, measured at  $3.79 \pm 0.53$  mm for c.w. and  $3.79 \pm 0.74$  mm for pulsed mode. In the periodontal tissues, lateral heat transfer

was  $6.13 \pm 0.85$  mm in c.w. mode and  $6.94 \pm 1.03$  mm in pulsed mode ( $p = 0.021$ ) (Figures 3 and 4).

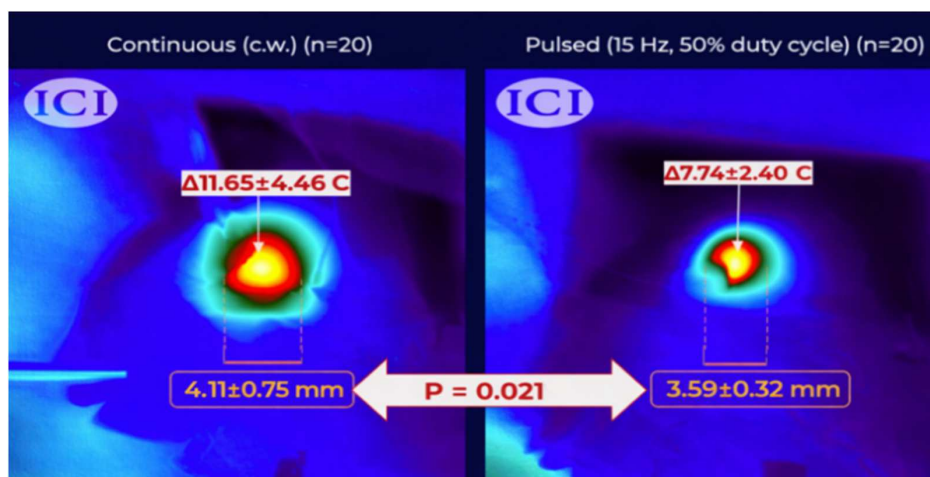
The vertical surface temperature distribution showed a similar pattern as periapical areas with minimal difference of  $4.56 \pm 0.85$  mm in c.w. and  $4.46 \pm 0.19$  mm in pulsed mode ( $p > 0.05$ ).

The statistical analysis demonstrated that lateral heat transfer in periapical tissues was lower compared to periodontal tissues. However, continuous waves showed greater heat transfer compared to pulsed modes in periapical tissues, whereas periodontal tissues showed the opposite. No significant difference was recorded when comparing vertical surface temperature distribution between continuous and pulsed modes in both periapical and periodontal tissues (Tables 1 and 2).

Analysis of the difference in groups displayed Cohen's d effect size of 1.51 and 1.09 for temperature changes in periodontal and periapical tissues, respectively. Because both values exceed

Figure 1

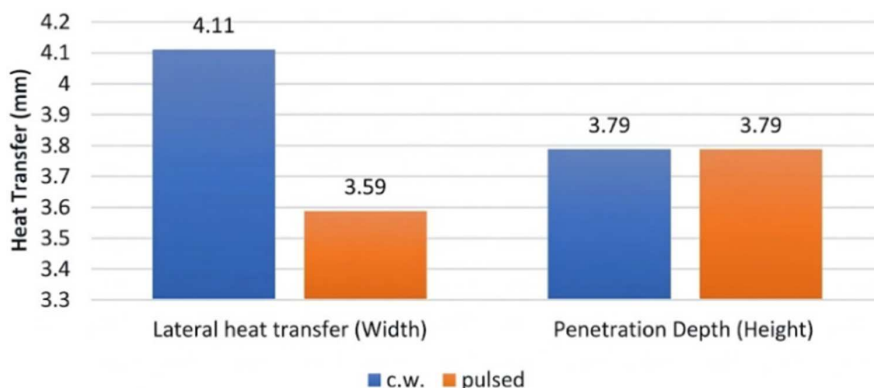
Irradiation of a root canal using a 445 nm diode laser results in periapical tissue heat transfer that propagates vertically along the root axis (penetration depth)



Note: Power: 2W. Glass fiber: 120 μm. 30 s irradiation. Non-initiated tips. Irradiation length as measured to 2/3 of peak heat transfer ( $p < 0.05$ ).

Figure 2

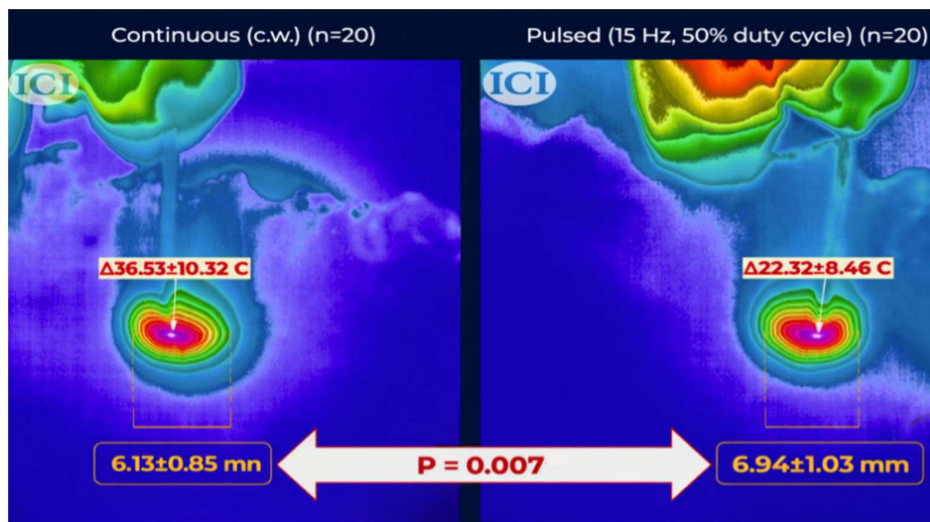
Results: heat transfer of 445 nm diode laser in periapical tissues



Note: Comparative statistics were calculated using the paired *t*-test for c.w. and pulsed modes at the 5% statistical significance level.

Figure 3

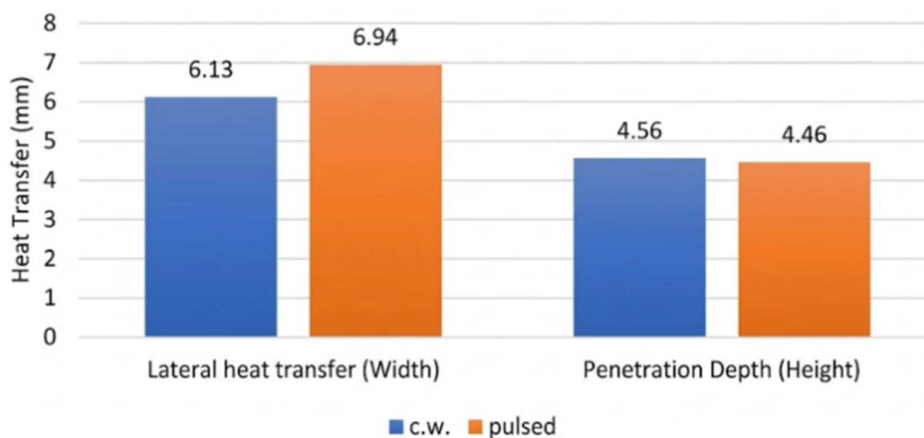
Irradiation of a periodontal pocket using a 445 nm diode laser produces periodontal tissue heat transfer, with the white/red central zone indicating the maximum temperature reached, while the surrounding gradient indicates the lateral heat transfer spreading to the alveolar bone



Note: Power: 2 W; Glass fiber: 320 μm. 30 s irradiation. Non-initiated tips. Irradiation length as measured to 2/3 of peak heat transfer ( $p < 0.05$ ).

Figure 4

Results: heat transfer of 445 nm diode laser in periodontal tissues



Note: Comparative statistics were calculated using the paired  $t$ -test for c.w. and pulsed modes at the 5% statistical significance level.

Table 1

Average lateral heat transfer and vertical surface temperature distribution in periapical tissue after 30 s of irradiation with 445 nm diode laser under c.w. and pulsed mode

	Lateral heat transfer (mm)		Vertical surface temperature distribution (mm)	
c.w.	$4.11 \pm 0.75$	$p = 0.021^{**}$	$3.79 \pm 0.53$	$p > 0.05$
Pulsed	$3.59 \pm 0.32$		$3.79 \pm 0.74$	

Note: The  $p$ -values indicate for analyzing the statistical differences between c.w. mode and pulsed mode (statistically significant).

**Table 2**  
Average lateral heat transfer and vertical surface temperature distribution in periodontal tissue after 30 s of irradiation with 445 nm diode laser under c.w. and pulsed mode

	Lateral heat transfer (mm)		Vertical surface temperature distribution (mm)	
c.w.	$6.13 \pm 0.85$	$p = 0.007^{**}$	$4.56 \pm 0.85$	$p > 0.05$
Pulsed	$6.94 \pm 1.03$		$4.46 \pm 0.19$	

**Note:** The  $p$ -values indicate for analyzing the statistical differences between c.w. mode and pulsed mode (statistically significant).

0.8, these findings indicate that there's a cooling effect in the pulsed mode clinically.

## 5. Discussion

The goal of the study was to evaluate the thermographic effect of a 445 nm diode laser on periodontal and periapical areas, specifically examining heat transfer from the anterior tooth canal to the periodontal tissues and from the periodontal tissues adjacent to molars to the surrounding structures. Using an ex vivo study and non-initiated fiber tips, we assessed the temperature change and lateral heat transfer under c.w. and pulsed delivery modes to better understand the thermal behavior of 445 nm irradiation in these periodontal and periapical areas.

In our study, we found that lateral heat transfer differed by tissue and mode: in periodontal tissues, pulsed mode produced significantly greater lateral spread than c.w., whereas in periapical tissues, c.w. produced significantly higher lateral heat transfer than pulsed mode. In addition, periodontal tissues had a significantly higher  $\Delta T$  (change in temperature) than periapical tissues, indicating greater peak temperature under similar measures. These findings suggest that the impact of 445 nm diode lasers on thermal distribution differs depending on tissue composition and delivery modes.

This is in agreement with the study by Wu et al. [18], who compared the temperature changes in homogenous bovine tongue tissue using initiated and non-initiated tips (2 W at 30 s). The authors confirmed that initiated tips produced greater  $\Delta T$  than non-initiated tips while vertical depth and lateral width at 30 s were similar between the different tips.

Periodontal tissues reached much higher peak temperatures (c.w.  $36.53 \pm 10.32$  °C; pulsed  $22.32 \pm 8.46$  °C) than periapical regions (c.w.  $11.65 \pm 4.46$  °C; pulsed  $7.74 \pm 2.40$  °C), indicating greater transfer of energy in periodontal sites. This is consistent with 445 nm high absorption efficacy for hemoglobin (main content of the red blood cells), which absorbs blue light more efficiently than collagen, thereby amplifying local thermal generation in highly vascular gingival tissues [6]. From a thermodynamic perspective, periodontal and periapical tissues have different thermal responses based on specific heat capacity ( $C_p$ ). Vascularized tissues such as periodontal tissue will have higher specific heat capacity compared to non-vascularized periapical areas [19]. Anatomically, the periodontal tissues are composed of gingiva, alveolar bone, cementum, and periodontal ligament, while periapical tissue consists of cementum, periodontal ligament, and alveolar bone [20, 21]. The gingiva is supplied with abundant intricate blood vessels, which is responsible for the vascularization and more vascularized than the periapical, non-inflamed tissues [22]. Consequently, the higher concentration of chromophores, along with high specific heat capacity in the

periodontal tissue, enhances absorption of the light in the 445 nm wavelength.

One factor that may explain the lower temperatures observed in the periapical tissues during tooth canal treatment is the nature of heat transfer and the thermal properties of the existing layers. When heat is generated within the tooth canal, it must traverse multiple layers—namely, the tooth structure, the bone, and finally the gingival tissue—before reaching the surface where the infrared thermographic camera records the temperature. According to Lin et al. [19], dentin has low thermal conductivity ( $k \approx 0.5$  W/m·K), and as the heat travels through the multiple layers of the tooth, it dissipates the heat and reduces the amount of heat reaching the surface. In contrast, during periodontal treatment, heat is generated beneath the gingival tissue and much closer to the surface, monitored by the thermographic camera, resulting in higher temperature readings. This difference in the path the heat takes could account for the higher temperatures observed in the periodontal tissues during laser irradiation. This was explained by Souza-Barros et al. [23] who demonstrated that the temperature elevation, transmittance, and reflectance were influenced during laser irradiation by the skin color and skin thickness.

Beyond vascular absorption differences, scattering effects may contribute to the lateral heat transfer result observed in this study. Laser–tissue interactions include absorption, reflection, transmission, and scattering. The scattering behavior of diode laser energy in soft tissues can be influenced by tissue hydration, vascularity, and the use of local anesthetics [24]. In their study, Romanos et al. [24] demonstrated that infiltration of water-based solutions, such as lidocaine and saline, significantly increased temperature rise in soft tissues during 810 nm or 980 nm diode laser irradiation. The 980 nm diode laser is highly absorbed by water. Specifically, at the wavelength of 980 nm, the absorption by water rises significantly compared to shorter wavelengths, and because hemoglobin absorption falls with increasing wavelength, the relative contribution of water to total absorption increases, so in many tissue contexts, water becomes the predominant absorber [25]. Thus, the fluid infiltration reduces the scattering within the tissue because primarily the water will be vaporized due to the high absorption by the 980 nm laser.

Under clinical settings, local anesthetics with vasoconstrictors may further influence thermographic behavior of the soft tissues. Our lab reported that lidocaine infiltration increased the magnitude of tissue temperature during c.w. diode laser exposure, particularly with non-initiated tips, due to fluid acting as a mechanical barrier leading to increased light scattering [24]. While our present experimental design did not involve a local anesthetic, periodontal tissues naturally contain more vasculature and interstitial fluid than periapical areas, which promotes absorption. While anesthetic-infiltrated tissues show increased lateral spread primarily due to fluid-induced scattering, periodontal tissues in our study demonstrated greater lateral heat transfer (periodontal

tissues: c.w.:  $6.13 \pm 0.85$  mm, pulsed:  $6.94 \pm 1.03$  mm) than periapical tissue (periapical tissues: c.w.:  $4.11 \pm 0.75$  mm, pulsed:  $3.59 \pm 0.32$  mm) through increased chromophore-driven absorption of 445 nm diode laser. In clinical settings, the vasoconstrictor-containing local anesthetic may influence the scattering effect and reduce chromophore absorption, which could further influence lateral heat transfer.

Another interesting finding is that the lateral heat transfer differed based on delivery modes and the tissue types: at the periapical areas, c.w. exceeded pulsed (c.w.:  $4.11 \pm 0.75$  mm, pulsed:  $3.59 \pm 0.32$  mm;  $p = 0.021$ ), whereas in periodontal tissues, pulsed exceeded the c.w. (c.w.:  $6.13 \pm 0.85$  mm, pulsed:  $6.94 \pm 1.03$  mm;  $p = 0.007$ ). In addition, there is no difference in the vertical surface temperature distribution when comparing the c.w. and pulsed modes in both tissues. Studies by Romanos et al. [26] analyzed pulsed vs. c.w. mode with both 980 nm and 445 nm diode lasers on the bovine gingiva; their results showed that c.w. mode has a greater vertical surface temperature distribution and thermal damage, which aligns with the results of the present study.

Our studies have shown that in every sample except periapical tissue in pulsed mode, the temperature changed by greater than  $10^\circ\text{C}$  (periodontal tissues: c.w.  $36.53 \pm 10.32^\circ\text{C}$ ; pulsed  $22.32 \pm 8.46^\circ\text{C}$  and periapical tissues: c.w.  $11.65 \pm 4.46^\circ\text{C}$ ; pulsed  $7.74 \pm 2.40^\circ\text{C}$ ) during the 30 s of irradiation. This signifies the importance highlighted in previous studies by Eriksson and Albrektsson [12, 13], which indicated that a threshold greater than  $10^\circ\text{C}$  for 1 min can injure bone and impair regeneration that can lead to nonreversible necrosis. The periodontal tissues displayed that regardless of the delivery mode, irradiation at 30 seconds leads to injury beyond the threshold. Our findings in periodontal tissues showed high lateral heat transfer, which could indicate clinical risk. Because the normal distance between the root surface and the alveolar bone is roughly 1–2 mm [20], large lateral heat transfer of greater than 6 mm can increase the likelihood of the bone reaching a temperature above the safety threshold of  $10^\circ\text{C}$ . In the current study, instead of assessing thermal damage histologically, it will be inferred from the temperature change induced by the laser as an indicator of tissue thermal damage. Given the 445 nm diode laser's ability to be absorbed by hemoglobin, maintaining a narrow margin is advised to limit the risk of injury. This is consistent with our results, which show that the pulsed mode reduces temperature change ( $36.5 \pm 10.3^\circ\text{C}$  to  $22.3 \pm 8.5^\circ\text{C}$ ) with a small increase in lateral spread ( $6.94 \pm 1.03$  vs  $6.13 \pm 0.85$  mm) in periodontal tissues, while producing greater lateral spread than continuous-wave (c.w.) mode. The reduction in temperature during pulsed mode aligns with the principles of Newton's Law of Heat Exchange (cooling) [27]. Pulsed mode allows thermal relaxation, preventing heat accumulation in adjacent tissues [28]. The reduction in temperature observed in the pulsed mode is primarily attributed to the 50% duty cycle, which effectively halves the average power delivered to the tissue compared to the c.w. mode. Given the 15 Hz frequency, this operates in a quasi-continuous thermal regime where significant tissue relaxation between pulses is unlikely. Therefore, the safety benefit observed is likely a function of reduced average energy density rather than a thermal relaxation mechanism specific to the pulse structure. Periapical areas still show greater temperatures than the threshold in c.w. delivery, but the lack of vasculature reduces the amount of heat absorbance compared to periodontal tissues.

## 6. Limitations

The present study has several limitations that should be addressed when interpreting the results. First, there is a methodological limitation of this *ex vivo* study as heat transfer in biological tissues is anisotropic, where thermal diffusion spreads along the x, y, and z-axes differently due to heterogeneity of tissues and tooth microstructure [29, 30]. In this study, heat transfer was measured with infrared thermography but only in a two-dimensional plane. In addition, the measurement of lateral heat transfer in millimeters should be interpreted as a macroscopic measurement along the same plane instead of a three-dimensional plane. However, by standardizing experimental conditions, we maintained a reliable comparison between tissues and delivery modes. Second, our study uses fixed power (2W) and irradiation time of 30 seconds as the parameters, which prevented us from performing regression analysis between energy input and tissue temperature. While our results were quantified with a paired *t*-test, future studies incorporating larger data sets and comparing a broader range of laser settings would benefit from a multi-factorial Analysis of variance (ANOVA) test and regression analysis analyzing thermal behaviors in a variety of clinical conditions. Additionally, structural differences between anterior and posterior mandibular segments, specifically variations in cortical bone thickness and root morphology, may have influenced the surface thermal patterns observed. Therefore, the differences between periodontal and periapical groups may reflect anatomical variations as well as tissue-specific thermal properties. This convective cooling effect could potentially dissipate heat and reduce peak temperatures in the *in vivo* model [19]. Future studies should investigate the effect of 445 nm diode lasers on inflamed clinical lesions in *ex vivo* models, mimicking the convective cooling effect. Finally, as an *ex vivo* study, tissues lacked perfusion and other biochemical and histological properties present in human oral mucosa compared to bovine tissue [27]. This could translate to a new thermal behavior and safety threshold, which indicates the importance of *in vivo* validation before any clinical trials. For future studies, a similar experimental study of the 445 nm diode laser could be conducted under *in vivo* conditions to mimic the blood supply to the gingiva.

## 7. Conclusion

Within the limitations of this study, it can be concluded that the 445 nm diode laser causes a higher temperature change in c.w. compared to pulsed modes, producing greater lateral heat transfer than apparent axial surface heat spread in periodontal and endodontic applications, with c.w. and pulsed modes producing site-specific differences.

## Acknowledgment

A preliminary version of this paper was previously published and presented by Dr. Jamie Wu as an abstract at the 2023 International Association for Dental, Oral, and Craniofacial Research (IADR/LAR) General Session with WCPD in Bogotá, Colombia [31]. The current manuscript represents an expanded and revised version of that abstract, including more detailed methodology and analysis of the results.

## Ethical Statement

This study does not contain any studies with human or living animal subjects performed by any of the authors.

## Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

## Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

## Author Contribution Statement

**Grace Kang:** Writing – original draft, Writing – review & editing, Visualization. **Jamie Wu:** Investigation. **Ghaedsharafi Yasamin:** Validation, Investigation. **Jiayue Han:** Writing – original draft, Writing – review & editing, Visualization. **Thomas Manders:** Validation, Investigation, Writing – review & editing. **Rafael Delgado-Ruiz:** Software, Validations, Formal analysis, Resources, Data curation, Writing – review & editing. **Georgios E. Romanos:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing – review & editing, Visualization, Supervision, Project administration.

## References

- [1] Malcangi, G., Patano, A., Trilli, I., Piras, F., Ciocia, A. M., Inchingolo, A. D., . . . , & Inchingolo, A. M. (2023). Therapeutic and adverse effects of lasers in dentistry: A systematic review. *Photonics*, 10(6), 650. <https://doi.org/10.3390/photonics10060650>
- [2] Sachelarie, L., Cristea, R., Burlui, E., & Hurjui, L. L. (2024). Laser technology in dentistry: From clinical applications to future innovations. *Dentistry Journal*, 12(12), 420. <https://doi.org/10.3390/dj12120420>
- [3] Inchingolo, A. M., Malcangi, G., Ferrara, I., Viapiano, F., Netti, A., Buongiorno, S., . . . , & Dipalma, G. (2023). Laser surgical approach of upper labial frenulum: A systematic review. *International Journal of Environmental Research and Public Health*, 20(2), 1302. <https://doi.org/10.3390/ijerph20021302>
- [4] Aoki, A., Ando, Y., Watanabe, H., & Ishikawa, I. (1994). In vitro studies on laser scaling of subgingival calculus with an erbium: YAG laser. *Journal of Periodontology*, 65(12), 1097–1106. <https://doi.org/10.1902/jop.1994.65.12.1097>
- [5] Fornaini, C., Fekrazad, R., Rocca, J.-P., Zhang, S., & Merigo, E. (2021). Use of blue and blue-violet lasers in dentistry: A narrative review. *Journal of Lasers in Medical Sciences*, 12, e31. <https://doi.org/10.34172/jlms.2021.31>
- [6] Frentzen, M., Kraus, D., Reichelt, J., Engelbach, C., Dehn, C., & Meister, J. (2016). A novel blue light diode laser (445 nm) for dental application: Biomedical testing and clinical aspects. *Laser*, 8(3), 6–13.
- [7] Kim, S., Kim, J., Lim, W., Jeon, S., Kim, O., Koh, J.-T., . . . , & Kim, O. (2013). In vitro bactericidal effects of 625, 525, and 425 nm wavelength (red, green, and blue) light-emitting diode irradiation. *Photomedicine and Laser Surgery*, 31(11), 554–562. <https://doi.org/10.1089/pho.2012.3343>
- [8] Gutknecht, N., Al Hassan, N., Martins, M. R., Conrads, G., & Franzen, R. (2018). Bactericidal effect of 445 nm blue diode laser in the root canal dentin on *Enterococcus faecalis* of human teeth. *Lasers in Dental Science*, 2(4), 247–254. <https://doi.org/10.1007/s41547-018-0044-1>
- [9] Lusche, I., Dirk, C., Frentzen, M., & Meister, J. (2020). Cavity disinfection with a 445 nm diode laser within the scope of restorative therapy—A pilot study. *Journal of Lasers in Medical Sciences*, 11(4), 417–426. <https://doi.org/10.34172/jlms.2020.66>
- [10] Ahrens, M., Spörer, M., Deppe, H., Ritschl, L. M., & Mela, P. (2024). Bacterial reduction and temperature increase of titanium dental implant models treated with a 445 nm diode laser: An in vitro study. *Scientific Reports*, 14(1), 18053. <https://doi.org/10.1038/s41598-024-68780-2>
- [11] Cercadillo-Ibarguren, I., España-Tost, A., Arnabat-Domínguez, J., Valmaseda-Castellón, E., Berini-Aytés, L., & Gay-Escoda, C. (2010). Histologic evaluation of thermal damage produced on soft tissues by CO<sub>2</sub>, Er, Cr:YSGG and diode lasers. *Medicina Oral Patología Oral y Cirugía Bucal*, 15(6), e912–e918. <https://doi.org/10.4317/medoral.15.e912>
- [12] Eriksson, A. R., & Albrektsson, T. (1983). Temperature threshold levels for heat-induced bone tissue injury: A vital-microscopic study in the rabbit. *The Journal of Prosthetic Dentistry*, 50(1), 101–107. [https://doi.org/10.1016/0022-3913\(83\)90174-9](https://doi.org/10.1016/0022-3913(83)90174-9)
- [13] Eriksson, R. A., & Albrektsson, T. (1984). The effect of heat on bone regeneration: An experimental study in the rabbit using the bone growth chamber. *Journal of Oral and Maxillofacial Surgery*, 42(11), 705–711. [https://doi.org/10.1016/0278-2391\(84\)90417-8](https://doi.org/10.1016/0278-2391(84)90417-8)
- [14] Eriksson, R. A., Albrektsson, T., & Magnusson, B. (1984). Assessment of bone viability after heat trauma. A histological, histochemical and vital microscopic study in the rabbit. *Scandinavian Journal of Plastic and Reconstructive Surgery*, 18(3), 261–268. <https://doi.org/10.3109/02844318409052849>
- [15] Pergolini, D., Palaia, G., de Angelis, R., Rocchetti, F., Podda, G. M., Tenore, G., . . . , & Romeo, U. (2023). SEM evaluation of thermal effects produced by a 445 nm laser on implant surfaces. *Dentistry Journal*, 11(6), 148. <https://doi.org/10.3390/dj11060148>
- [16] Gutiérrez-Corrales, A., Rizcala-Orlando, Y., Montero-Mirallas, P., Volland, G., Gutiérrez-Pérez, J. L., Torres-Lagares, D., & Serrera-Figallo, M. A. (2020). Comparison of diode laser – Oral tissue interaction to different wavelengths. In vitro study of porcine periodontal pockets and oral mucosa. *Medicina Oral Patología Oral y Cirugía Bucal*, 25(2), e224–e232. <https://doi.org/10.4317/medoral.23317>
- [17] Hohmann, M., Kühn, D., Ni, D., Späth, M., Ghosh, A., Rohde, M., . . . , & Schmidt, M. (2024). Relevant parameters for laser surgery of soft tissue. *Scientific Reports*, 14(1), 1263. <https://doi.org/10.1038/s41598-024-51449-1>
- [18] Wu, J., Roibu, E. G., Hou, W., Delgado-Ruiz, R., & Romanos, G. E. (2024). Thermal effects of 445 nm laser irradiation on the bovine tongue tissues ex vivo. *Journal of Optics and Photonics Research*, 2(3), 145–152. <https://doi.org/10.47852/bonviewJOPR42022543>
- [19] Lin, M., Xu, F., Lu, T. J., & Bai, B. F. (2010). A review of heat transfer in human tooth—Experimental characterization and mathematical modeling. *Dental Materials*, 26(6), 501–513. <https://doi.org/10.1016/j.dental.2010.02.009>
- [20] Fiorellini, J. P., Kao, D. W. K., Kim, D. M., & Uzel, N. G. (2023). Anatomy of the periodontium. In M. G. Newman, P.

- R. Klokkevold, S. Elangovan, Y. Kapila, F. A. Carranza, & H. Takei (Eds.), *Newman and Carranza's clinical periodontology and implantology* (14th ed., pp. 11–13). Saunders.
- [21] Omami, G., & Wiggins, R. H. (2024). Inflammatory lesions of the jaws. *Dental Clinics of North America*, 68(2), 259–276. <https://doi.org/10.1016/j.cden.2023.09.003>
- [22] Koller, A., & Sapra, A. (2023). *Anatomy, head and neck, oral gingiva*. USA: StatPearls Publishing.
- [23] Souza-Barros, L., Dhaidan, G., Maunula, M., Solomon, V., Gabison, S., Lilge, L., & Nussbaum, E. L. (2018). Skin color and tissue thickness effects on transmittance, reflectance, and skin temperature when using 635 and 808 nm lasers in low intensity therapeutics. *Lasers in Surgery and Medicine*, 50(4), 291–301. <https://doi.org/10.1002/lsm.22760>
- [24] Romanos, G. E., Tedesco, R. W., Malhotra, U., Hong, H., Hou, W., & Delgado-Ruiz, R. (2021). Diode laser light scattering and temperature changes due to anesthesia injection in bovine tongue mucosa. *Photobiomodulation, Photomedicine, and Laser Surgery*, 39(9), 587–592. <https://doi.org/10.1089/photob.2020.4989>
- [25] Matcher, S. J., Cope, M., & Delpy, D. T. (1994). Use of the water absorption spectrum to quantify tissue chromophore concentration changes in near-infrared spectroscopy. *Physics in Medicine and Biology*, 39(1), 177–196. <https://doi.org/10.1088/0031-9155/39/1/011>
- [26] Romanos, G. E., Estrin, N. E., Lesniewski, A., McClain, S., & Hou, W. (2022). Penetration depth of initiated and non-initiated diode lasers in bovine gingiva. *Applied Sciences*, 12(24), 12771. <https://doi.org/10.3390/app122412771>
- [27] Zhao, B. (2022). Integrity of Newton's cooling law based on thermal convection theory of heat transfer and entropy transfer. *Scientific Reports*, 12(1), 16292. <https://doi.org/10.1038/s41598-022-18961-8>
- [28] Parker, S., Cronshaw, M., Anagnostaki, E., Mylona, V., Lynch, E., & Grootveld, M. (2020). Current concepts of laser-oral tissue interaction. *Dentistry Journal*, 8(3), 61. <https://doi.org/10.3390/dj8030061>
- [29] Bedoya, A., Salazar, A., Mendioroz, A., & Marin, E. (2024). Measuring the in-plane thermal diffusivity of anisotropic solids by lock-in infrared thermography: Laser-spot vs laser-line heating. *Journal of Applied Physics*, 135(13), 135102. <https://doi.org/10.1063/5.0198882>
- [30] Lin, M., Liu, Q. D., Kim, T., Xu, F., Bai, B. F., & Lu, T. J. (2010). A new method for characterization of thermal properties of human enamel and dentine: Influence of microstructure. *Infrared Physics & Technology*, 53(6), 457–463. <https://doi.org/10.1016/j.infrared.2010.09.004>
- [31] Wu, J., Ghaedsharafi, Y., Manders, T., Delgado-Ruiz, R., & Romanos, G. (2023). Thermographic effects of 445 nm-laser in periodontal and periapical areas. In *2023 IADR/LAR General Session with WCPD*. <https://iadr.abstractarchives.com/abstract/23iags-3893440/thermographic-effects-of-445nm-laser-in-periodontal-and-periapical-areas>

**How to Cite:** Kang, G., Wu, J., Yasamin, G., Han, J., Manders, T., Delgado-Ruiz, R., & Romanos, G. E. (2026). Thermographic Effects of 445 nm Laser in Periodontal and Periapical Areas Ex Vivo. *Journal of Optics and Photonics Research*. <https://doi.org/10.47852/bonviewJOPR62028553>