



Measurement of Light Power from 940 nm Diode Laser Transmitted Through Tooth Crown

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Abstract

Introduction: Light transmission in biological tissues is used in many subsurface intervention applications, such as photobiomodulation, fluorescence, and laser Doppler flowmetry. The aims of the current study were to measure the light power of a 940-nm diode laser transmitted through dental crowns and to correlate this transmission with crown thickness.

Methods: Thirty non-carious extracted human premolar longitudinal-half-crown sections were used in this experiment. The laser device was operated in continuous wave mode at 0.59 W for 10 s. The power density was 468.25 W/cm², and the irradiation dose was 4682.5 J/cm² at the laser tip. The laser irradiation was applied twice to each sample, on the external crown surface and the pulpal surface. The transmitted laser power through the tooth crown was measured using a power meter.

Results: Descriptive statistics indicated a transmitted power of 0.044 ± 0.018 W when the external surface of the tooth was irradiated and 0.164 ± 0.039 W when the pulpal side was irradiated. Spearman correlation analysis revealed a non-significant negative relationship between sample thickness and transmitted laser power in the externally irradiated group ($r = -0.111$, $P = 0.558$) and a significant negative relationship in the pulpal irradiated group ($r = -0.637$, $P = 0.000$).

Conclusion: The laser power transmission was four times greater after irradiation of the pulpal side than the external side. Our findings demonstrated that laser transmission is inversely associated with tooth thickness.

Keywords: Diode laser, Transmission, Power, Dental crown

Introduction

The complex structures of enamel and dentin affect light transmission. Light transmission through dental hard tissue has many applications. For example, photobiomodulation uses wavelengths in the red range (600 – 700 nm) and the near infrared (IR) range of 800 - 1100 nm to treat dentin hypersensitivity, thereby achieving local analgesia, accelerating healing, and decreasing inflammation.^{1,2} Another application is high-power laser treatment (for example, 940 nm) for root canal disinfection. This wavelength achieves root canal disinfection and subsequent pain reduction.³ In addition, light transmission is used in various applications and diagnostics; for example, laser Doppler flowmetry has been applied to measure pulp vitality.⁴ Understanding light transmission through dental hard tissue can aid in adjusting laser settings and achieving accurate diagnosis.⁵

The optical properties of enamel and dentin, such as their absorption, scattering, and anisotropy, influence light transmission. Enamel and dentin are semi-transparent tissues showing high scattering of light in the visible and near IR regions of the electromagnetic spectrum. Fried et al. have found that enamel scatters light weakly in the visible and near-infrared (NIR) wavelengths, and dentin scatters

light strongly in these wavelengths.⁶ Absorption of the visible and NIR wavelengths of light is low in dental hard tissue and occurs primarily in organic components, such as protein. The peak absorption is below 500 nm.⁷ Scattering, the main process occurring when light interacts with dental hard tissue, is due to the refractive index disharmony when light interacts with the dentinal tubules or enamel prisms.⁸ The scattering coefficients range between 10 and 200 cm⁻¹ in the visible wavelengths.^{9,10} Scattering decreases in the NIR range of 800 to 1000 nm; consequently, deep penetration as far as 10 mm occurs, whereas shorter wavelengths may penetrate only 2 mm.^{11,12}

Dentin is an anisotropic tissue because of the dentinal tubule orientation. These tubules diverge as they run toward the dentino-enamel junction. Consequently, light behavior differs according to the direction of light application. Walton et al. observed a magnified image when light was directed from pulp toward the external area, owing to the divergence of dentinal tubules as they reach the dentino-enamel junction. The dentinal tubules guide light, particularly when the light is directed from the pulp direction toward the external area.¹³ Odor et al. have reported that light follows the path of dentinal tubules and enamel prisms because of effective coupling between light

and these structures. The dentinal tubules and enamel prisms receive light and transport it across the dental hard tissue, thus explaining why light is transmitted through dental hard tissue despite tooth thickness and the high coefficient of scattering. This behaviour has been used in many dental applications, such as light transillumination and laser Doppler flowmetry.¹⁴ Previous research has indicated that light is transported in dental hard tissue through total internal reflection because the dentinal tubules act as a waveguide for the light. After interacting with the dentinal tubules, light is transported across dentin through multiple scattering, as explained by Monte Carlo simulations indicating that the light follows the path of these tubules.¹⁵

This study was aimed at exploring how much of the power of a 940 nm laser is transmitted through dental hard tissue in an intact crown, whereas many prior studies have been conducted on teeth sectioned to 1 mm, to accommodate spectrometer limits.¹⁶ Because teeth differ in thickness, knowing how much light reaches the dental pulp is important, as it affects the biomodulation dose and consequently clinical outcomes.

The 940-nm diode laser has clinical relevance in dental applications, including endodontic disinfection, soft-tissue procedures, and biomodulation. The therapeutic window between 700 and 1400 nm has low absorption in dental hard tissues,^{6,8,17,18} enabling wavelengths within this range to penetrate deeply or transmit through them. This property enables subsurface applications such as root canal disinfection or biomodulation of pulpal tissues.

Limited data have indicated the quantity of power of a 940-nm laser that reaches the subsurface and the effect of thickness on light transmission. Filling this knowledge gap is important to determine the extent of compensation for losses in the energy of light passing through dental hard tissue, as well as to avoid administering either ineffective sub-therapeutic doses or overdoses that cause thermal damage.

The goal of the current study was to measure the light power of a 940-nm diode laser transmitted through a dental crown and to correlate this transmission with crown thickness. To achieve this objective, we measured 940-nm laser power transmission through a tooth crown. Longitudinal sections of premolar crowns were used to simulate a clinical scenario. We hypothesized that laser irradiation on the pulpal side would achieve greater transmission, because of the favorable orientation of dentinal tubules, and that this transmission would inversely correlate with tooth thickness. Our findings of how much light power reaches the pulp might aid in laser parameter adjustment to ensure safety and efficacy.

Materials and methods

Sample preparation

Fifteen non-carious extracted human premolar teeth were used in this experiment; these teeth were extracted for orthodontic reasons. This study was approved by the ethics committee of Al-Hadi University, College of

Dentistry, project no. 1.9/2024. Under running water, the teeth were sectioned at the cemento-enamel junction with a low-speed diamond disk (915/DC; Meisinger, Germany). Subsequently, each crown was sectioned longitudinally into halves, thus resulting in 30 samples. After sectioning, the remaining pulp tissue was removed gently with a spoon excavator, and the sections were rinsed with 2-mL normal saline and stored in normal saline at 4 °C.

Laser irradiation settings

This experiment used a 940-nm diode laser (Epic™ 10, Biolase Inc., Irvine, CA, USA). The laser energy was delivered with an E4-4 plain-end surgical tip with a fiber diameter of 400 µm. The laser device was operated in continuous wave mode at 0.59 W (laser display= 1 W) for 10 seconds. The power density was 468.25 W/cm², and the irradiation dose was 4682.5 J/cm² at the laser tip. The output power was calibrated with a power meter detector (UP25N-100H-H9, Maestro, Gentec Electrooptic Inc., QC, Canada). Due to the presence of coupling losses between the optical fibre and the laser tip) fibre transmission losses and laser tip losses(, all above laser settings calculations were based on the calibrated output, not the display value to ensure the accuracy of the laser parameters calculations. Laser irradiation was performed in a stationary mode at a 1-mm distance perpendicular to the tooth surface. The laser handpiece was stabilized using a laboratory clamp holder. The laser was applied to the middle of external and pulpal sides of each sample (Table 1).

Measurement of transmitted power

During laser irradiation, the samples were positioned over the power meter detector with a double layer of aluminum foil containing a 6 × 4 mm window and one layer of articulating paper to prevent recording of ambient noise signals. The recording was acquired with a sample rate of 10/s from the power meter via USB storage. The samples were irradiated directly after removal from the normal saline storage solution (Figure 1). After irradiation,

Table 1. Laser irradiation settings

Settings (unit)	Value
Type of laser	Diode
Wavelength (nm)	940
Emission Mode	CW
Time on (S)	10
Delivery system	Fiber optic
Average power (W)	0.59
Spot diameter at focus (cm)	0.04
Focus spot area (cm ²)	0.00126
Power density (W/cm ²)	468.25
Energy (J)	5.90
Fluency (J/cm ²)	4682.5
Beam divergence (° / side angle)	7 - 22
Water irrigation	None
Air and aspirating airflow	None

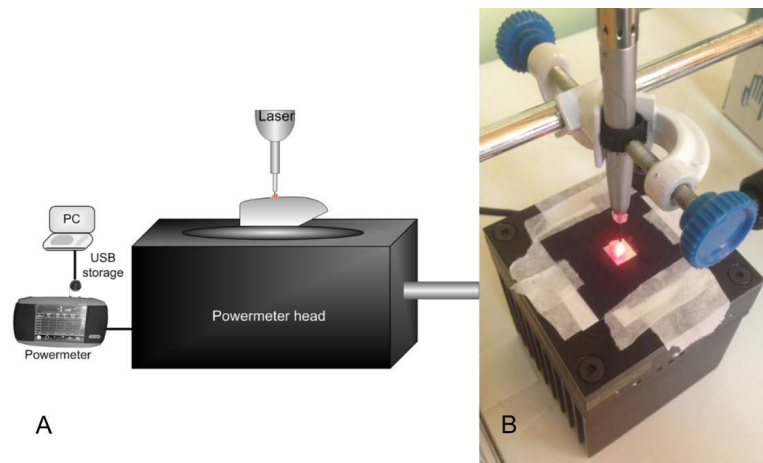


Figure 1. The experimental setup for transmitted power measurement. A Schematic illustration of experiment setup: the powermeter head is positioned parallel to the crown's vertical axis, and the direction of power transmission is horizontal. B Actual view of experiment setup

sample thickness was measured from the enamel surface to the pulp roof with digital Vernier calipers (TOPEX Sp. z o.o. S.K., Warsaw, Poland), with a resolution of 0.01 mm and accuracy of ± 0.02 mm. Sample thickness was measured three times, and the average was considered in further statistical analyses.

Statistical analysis

We first used the Shapiro-Wilk normality test to determine differences between paired measurements. This experiment was conducted in a paired scheme, in which each sample was irradiated twice: once on the external side and once on the pulpal side. Accordingly, a related-samples Wilcoxon signed rank test was used to identify significant differences between treatment groups. The Spearman correlation test was applied to evaluate the relationship between transmitted power and sample thickness. The significance threshold was 0.05.

Results

Descriptive statistics indicated a transmitted power of 0.044 ± 0.018 W when the external surface of the tooth was irradiated and 0.164 ± 0.039 W when the pulpal side was irradiated. The minimum, maximum, and standard error are shown in Table 2.

Shapiro-Wilk normality testing indicated that the groups' measurement readings were not normally distributed ($P=0.043$); consequently, the related-samples Wilcoxon signed rank test was performed. A statistically significant difference ($P=0.000$) was observed between the external and pulpal irradiation test groups (Figure 2).

The descriptive statistics of the samples' thickness measurement, starting from the enamel surface to the pulp roof, indicated a mean of 3.09 ± 0.23 mm, and minimum and maximum sample thicknesses of 2.62 and 3.56 mm, respectively. Spearman correlation analysis revealed a non-significant negative relationship between sample thickness and transmitted laser power in the external irradiated group ($r = -0.111$, $P=0.558$) and significant negative one for the pulpal irradiated group ($r = -0.637$, $P=0.000$) (Figures 3 and 4).

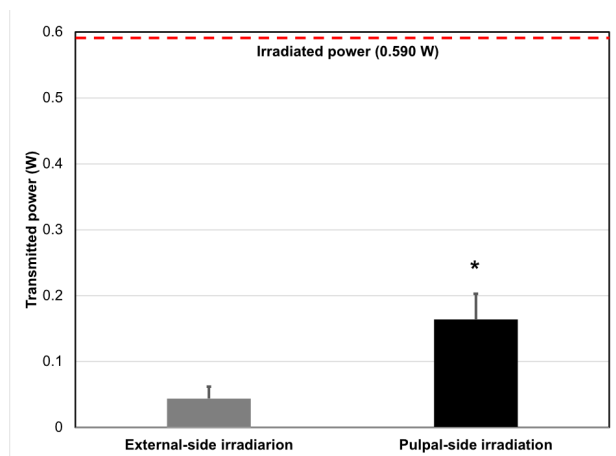
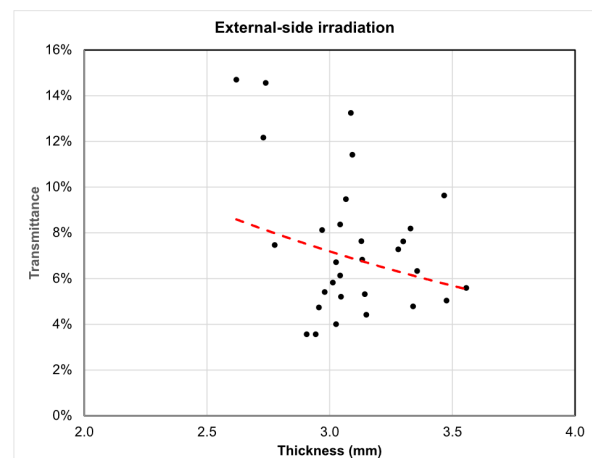
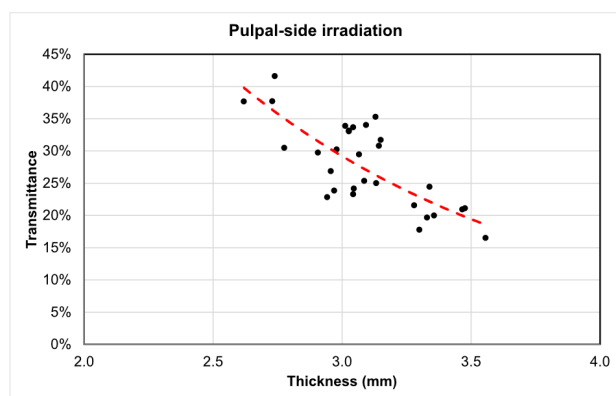
Discussion

Herein, we observed that a small fraction of 940-nm laser power was transmitted through the dental hard tissue (7% and 28% for externally and pulpally directed laser irradiation, respectively). The laser power transmission was four times greater after laser irradiation of dental hard tissue on the pulpal side than the external side. The dental tissue significantly attenuated the power of the 940-nm laser. According to previous studies, only several percent of incident power is transmitted through several millimeters of tooth structure. Watanabe et al. have observed that only 2% and 3% of incident light is transmitted through a tooth crown with a thickness of 3 mm irradiated with 632 and 830 nm wavelengths, respectively.^{19,20} Chan et al. have measured 8% and 7% transmission of 810-nm and 980-nm lasers, respectively, through tooth crowns.²¹ Kulkarni et al. have measured the transmitted power of 660-nm, 808-nm, and 904-nm lasers through a 3-mm-thick tooth crown, and the results were ~1 - 2, 3, and 3 - 4% for the 660-nm, 808-nm, and 904 nm lasers, respectively.²² In the current study, although a different wavelength was used, during external side irradiation, the transmitted power of 940 nm was 7%, in agreement with previous studies. We observed an inverse exponential relation between transmitted power and tooth thickness when the laser was irradiated toward the pulpal side, because of cumulative scattering and absorption of laser light energy, as supported by previous studies.¹⁹⁻²¹ This observation is explained by Beer-Lambert's law of light propagation. In comparison, the aforementioned studies performed laser irradiation on the external side of the tooth crown. We found no studies irradiating the opposite side (pulpal) for comparison with the current study results.

Tooth structure is anisotropic, which means that laser irradiation is directionally dependent. Herein, the finding of higher transmitted power during pulpal side than external side irradiation might be explained by the high density of dentinal tubules at the pulpal surface of dentin. These tubules serve as guides for light transportation, which occurs through direct coupling between light and dentinal tubules. During irradiation of the external surface, the light encounters the enamel barrier before it reaches the

Table 2. Descriptive statistics of transmitted power measurements (W) in the experimental groups

Groups	N	Mean	Standard deviation	Standard error	Minimum	Maximum
External irradiation	30	0.044	0.018	0.003	0.021	0.087
Pulpal irradiation	30	0.164	0.039	0.007	0.098	0.245

**Figure 2.** Graphical illustration of a bar chart showing the mean values for the transmitted power of the external and pulpal-side 940-nm diode laser irradiation (n=30), * = Significant difference at 0.05**Figure 3.** Scatter plot of external-side irradiation of the crown illustrating the relationships between transmittance (%) and thickness (mm). The red dotted line indicates the exponential line of best fit. $r = -0.111$, $P = 0.558$, $n = 30$ **Figure 4.** Scatter plot of pulpal-side irradiation of the crown illustrating the relationships between transmittance (%) and thickness (mm). The red dotted line indicates the exponential line of best fit. $r = -0.637$, $P = 0.000$, $n = 30$

dentinal tubules. Because the dentinal tubules are less dense near the external side than the pulpal side of dentin, light irradiation on the pulpal side favors the coupling of light to the dentinal tubules. In contrast, when light is irradiated on the external side, the direction of light is less favorable for light travel because of the orientation of the dentinal tubules, which start to diverge as they reach the external side of dentin. This explanation is further supported by experiments conducted by Walton et al. and Kienle et al, who have reported a magnification of the transmitted light image as the path of dentinal tubules diverges toward the external surface, and vice versa.^{13,15} An experiment by Kienle et al. has confirmed the anisotropy of light, which is guided by multiple scattering when it interacts with the dentinal tubules. This behavior of light has been described through a Monte Carlo simulation of light transmission.¹⁵ Another factor that may influence light transmission is light reflection at the air-tooth interface and the enamel-dentin interface. At the air-enamel interface, the mismatch

in the refractive index is higher compared to that of the air-dentin interface. The refractive index are $n = 1.63$ and 1.54 for enamel and dentin, respectively.²³ By calculating the reflection of light at enamel and dentin surfaces using the Fresnel equation at normal incidence, we found that that reflectance R is 5.75% for enamel and 4.52% for dentin, which further indicates higher transmission when the tooth crown is irradiated from the pulpal side than from the external side. At the enamel-dentin interface, the refractive index mismatch between enamel and dentin is too small making the Fresnel reflection negligible. However, during the external irradiation side when part of the incident light angle coincides with the critical angle, a total internal reflection may occur. When the laser is irradiated the pulpal side, total internal reflection is not applicable at the dentin-enamel interface, as total internal reflection requires light to be transmitted from a higher refractive index tissue (enamel) to a lower one (dentin).

Referring to the above calculation that shows only a small part of light is reflected and owing to the small absorption coefficient of enamel and dentin at near-IR ($\mu_a = 1 \text{ cm}^{-1}$ and 4 cm^{-1} for enamel and dentin, respectively), the main laser-tissue interaction of 940-nm laser light inside dental hard tissue is scattering. Herein, dentin has a higher scattering coefficient ($\mu_s = 260 \text{ cm}^{-1}$) than that of enamel ($\mu_s = 15 \text{ to } 105 \text{ cm}^{-1}$) at near-IR.⁶

The limitations of the current study include that only premolar teeth were used, and the obtained findings therefore cannot be applied to other tooth types, such as thick molars or thin incisors. In addition, the study focused on immediately transmitted power and did not account for thermal or temporal phenomena, which might be explored in future research. Finally, the presence of pulp or periodontal tissue might absorb or scatter transmitted

light but could not be determined in the current study.

Most incident laser energy is lost through scattering and absorption within dental hard tissues. Achieving therapeutic doses in pulp photobiomodulation (e.g., to accomplish analgesia, healing of pulp exposure, and dentin disinfection) requires laser power adjustment to compensate for the losses and consideration of collateral thermal effects on the surrounding tissue. In the current study, the samples were kept moist during laser irradiation; otherwise, air-filled dentinal tubules would increase scattering and may alter light transmission clinically. An irradiation power of 0.59 W was chosen because it is a clinically used setting for near-IR dental diode lasers, for example, in tooth hypersensitivity and root canal disinfection. Moreover, this level of power will ensure that the tissue's safe thermal limits are met in the *in vitro* experiment.^{24,25}

Notably, the safe therapeutic window can be narrow, as explained by the Arndt-Schultz law: when the power is too low, no therapeutic effect occurs, whereas when the power is too high, the therapeutic effects decline, and thermal adverse effects may occur. Moreover, laser settings must be modified according to tooth thickness. Herein, we observed a steep decline in transmitted power with increasing thickness.

Future studies should extend the current findings to include different wavelengths and power settings and tooth types, including teeth with restorations, and to explore the biological effects of transmitted power on surrounding tissues. Integrating the findings from such *in vitro* studies with the biological effects observed *in vivo* might enable the development of evidence-based protocols to ensure operation within therapeutic and safe limits for tissues.

In conclusion, this study explored the interaction between a 940-nm diode laser and tooth hard tissues by calculating laser power transmission through the tooth crown under irradiation from the external and pulpal sides with this laser. The laser power transmission was four times greater when the pulpal side was irradiated rather than the external side. Our findings demonstrated a significant association between laser transmission and tooth thickness.

Authors' Contribution

Conceptualization: Mohammed Abbood Al-Maliky, Tamara Sardar Al-Karadaghi

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Validation: Mohammed Abbood Al-Maliky, Tamara Sardar Al-Karadaghi

Visualization: Mohammed Abbood Al-Maliky

Writing – Original Draft: Mohammed Abbood Al-Maliky

Writing–Review & Editing: Mohammed Abbood Al-Maliky, Tamara Sardar Al-Karadaghi

Competing Interests

The authors have no competing interests to declare that are relevant to the content of this article.

Ethical Approval

The study protocol was approved by the Al-Hadi University institutional review board (project no. 1.9/2024). All procedures involving human participants were conducted in accordance with the ethical standards of the 1964 Helsinki Declaration and its subsequent amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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