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ORIGINAL ARTICLE

Quantifying light energy from 450 nm, 650 nm, 810 nm, and 980 nm wavelength lasers delivered through dental hard tissue

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Abstract

Purpose The energy available to treat the dental pulp after transmittance through overlying structures is clinically important for determining photobiological effects. This ex vivo study aimed to quantify laser energy delivery though the dental crown to the pulp from an initial energy of 5 J using four common laser wavelengths ($\lambda = 450$, 650, 810, and 980 nm).

Material and methods A total of 30 extracted healthy human teeth (anterior $n = 10$; premolar $n = 10$; molar $n = 10$) were longitudinally sectioned (Project Number: 2021/421, University of Sydney, NSW, Australia). Each sample was methodically exposed in random order to the four wavelengths. Each wavelength was operated at the same power (0.50 W) for 10 s to deliver 5.0 J with a total energy delivery of 10 J/cm^2. Laser light was delivered with an 8-mm-diameter fiber bundle probe directed perpendicularly to the buccal cervical-third of the crown. The transmitted energy was measured twice and averaged using a periodically pre-calibrated power meter in blinded conditions. Data were analyzed using a general linear model with logarithmic transformation.

Results Wavelength and tooth thickness were significant predictors of optical transmittance ($P < 0.05$) while tooth type was significant only for the 450 nm wavelength. The average attenuation coefficients (μ) were 2.55, 2.45, 1.87, and 5.42 cm^{-1} ($\pm$ 10%) for the 980, 810, 650, and 450 nm groups, respectively.

Conclusion Clinicians should recognize that significant attenuation occurs during laser energy delivery to the pulp, influenced by the wavelength, thickness, and tooth type. Our findings support the potential for laser energy delivery to the pulp for photobiomodulation applications.

Keywords Photobiomodulation · Tooth crown · Laser transmittance · Blue wavelength · Red wavelength · Near-infrared wavelength

Introduction

The adjunctive use of lasers in the field of dentistry for diagnosis and treatment has led to improved clinical outcomes. While laser treatment appears to be a relatively simple intervention, a plethora of parametric variables can influence such outcomes, including wavelength, energy and power density, laser pulse profile, duration, total energy and power, spot size, and tissue absorption characteristics [1]. Overlooking the nuances in these variables has inadvertently contributed to a lack of standardized treatment parameters [2]. By improving our understanding of how light transmits though intrinsically complex dental structures [3], we can optimize and tailor parameters to facilitate safe and effective clinical treatment.

Many dental laser applications involve irradiation through the dental crown. Applications of red and near infra-red (NIR) lasers include treating dentine hypersensitivity [4], achieving pre-operative anesthesia [5], and promoting pulp vitality in regenerative endodontics [6]. Such applications are collectively known as low-level laser therapy or photobiomodulation therapy, which uses light in the red ($\lambda = 600$–700 nm) or NIR region ($\lambda = 780$–1100 nm) with a

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power density between 5 mW cm^{-2} and 5 W cm^{-2} [7]. Clinical applications include promoting healing and regeneration, decreasing inflammation, and achieving analgesia [8].

Likewise, the application of blue wavelength lasers ($\lambda = 400–500$ nm) for preventative [9], restorative [10], and soft-tissue surgical procedures [11], all frequently result in coronal irradiation. In particular, the polymerization of dental composites using blue lasers at wavelengths targeting the camphorquinone initiator system ($\lambda = 468$ nm) is routinely practiced [12]. Compared to halogen and light emitting diode (LED) light curing units, the precise delivery of a sharply defined high-intensity laser light offers better energy efficiency, quality of irradiation, and degree of conversion [12, 13].

Whenever the crown is irradiated, it is valuable to determine the quantity of light that reaches the pulp, after its interaction with overlying tissues (transmission, reflection, absorption, and scattering), as this dictates the photobiological effects [3]. Blue, red, and NIR wavelengths all have the potential for photobiomodulation effects [14]. Moreover, both high-power and low-power lasers have potentially stimulating or inhibiting, desirable or unfavorable consequences [15]. This is consistent with the biphasic curve response of biological tissues, also termed the "Arndt Schulz Law", where light stimulus in excess or deficiency of the optimal dose leads to the effect being inhibited or weakened, respectively [16].

A recent systematic review into photobiomodulation dose parameters in dentistry cautioned that significant attenuation, also termed "optical transport", occurs through biological tissues resulting in energy loss and diminished clinical outcomes [17]. While it has been proposed that a higher surface-level dose be adopted for sub-surface treatment [17], we currently lack sufficient information as to how much light energy reaches the pulp and its relationship with other tooth-related variables.

The absorption, scattering, and transmission spectra of enamel and dentine have been investigated in several studies. Fried et al. determined the scattering and absorption coefficients of enamel and dentine [18], building upon the research conducted by Spitzer et al. [19]. Later, Belikov et al. reported the absorption spectra of intact human tooth enamel and dentine using a spectrometer with processed enamel and dentine samples [20]. Dogandzhiyska et al. used a spectrometer to measure the absorption and transmission spectra of 1-mm-thick occlusal dentin sections [21]. Pop-Ciutrila et al. used a spectroradiometer to evaluate the spectral behavior of dentine and compared various tooth types [22]. Such studies have provided valuable insight into absorption bands and other important optical characteristics of enamel and dentine.

Despite the potential for the existing spectra to be used to tailor photobiomodulation therapies, in clinical practice, it remains underutilized due to the difficulties of chairside integration. Previous studies have been necessarily conducted on thin or modified sections due to the sensitivity of spectrometric techniques, where larger samples displace or distort the spectrometer beam [23]. We cannot assume a direct relation between a thin sample and an intact tooth [24], especially with the complex structural variations within a tooth and between different teeth. Spectral data are limited for wavelengths relevant for photobiomodulation, as previous studies have focused on the visible spectrum ($\lambda = 400–700$ nm) [22, 25, 26]. Moreover, spectral data are currently impractical for tailoring chairside laser applications due to the combination of absorbers (protein, hydroxyapatite, water etc.) and scatterers (hydroxyapatite, dentine tubules), the respective coefficients, and possibility of tooth-related variations [26]. Therefore, if we intend to improve the clinical applicability of existing research to guide clinicians, there is a need to calculate the laser energy delivery through intact tooth samples at wavelengths relevant to photobiomodulation, over a range of thicknesses [24].

Accordingly, the primary aim of this study was to quantitatively determine how much laser energy is delivered through the dental crown to the pulp from a standardized initial energy of 5 J, using four widely used laser wavelengths ($\lambda = 450$, 650, 810, and 980 nm). The dose parameters were derived from existing clinical reports [5, 27] within which there is a wide variation in protocols [24]. The secondary outcome was to assess the effect of wavelength, tooth thickness, and tooth type on the quantity of energy delivery.

Materials and methods

Thirty unrestored non-carious extracted human teeth, consisting of anterior ($n = 10$), premolar ($n = 10$), and molar ($n = 10$) teeth, were collected from patients of Westmead Hospital. Approval from the Human Research Ethics Committee was obtained prior to sample collection (Project Number: 2021/421, University of Sydney, NSW, Australia). Sample size calculation was completed using G*Power 3.1 (effect size f: 0.40; α error probability: 0.05; power (1-β error probability): 0.80). Teeth were longitudinally sectioned using a Buehler linear precision saw (Isomet 5000) and the buccal cut surfaces were hand-sanded to 1200 microns. Samples were preserved at 4 °C in 4% saline to avoid scattering changes due to drying.

Measurements of the maximum crown thicknesses were taken between the enamel surface and the dentino-pulpal junction at the buccal cervical third of the crown, averaged and recorded, using a dental caliper (Salvin Dental Specialties, Inc, Charlotte, North Carolina, USA) by two independent examiners.

Laser wavelengths, parameters validation, and equipment

The power outputs of the laser devices were quantitatively validated prior to every measurement using a thermal power sensor (Thorlabs S310C) with PM200 meter which was pre-calibrated (± 0.002 W) using a thermopile sensor (Newport 843-R) at the MQ Photonics Research Centre, Macquarie University. The beam area profiles of the laser fiber-bundle probe were measured in a previous study [28]. Each of the wavelengths was operated at the same power (0.50 W) for 10 s to deliver 5.0 J with a total delivered energy fluence of 10 J/cm^2. The parameters of each laser wavelength were fully recorded in Table 1.

Measurement of laser energy delivery to the pulp

The order of the laser wavelength employed was randomly selected by the throw of a die. Two independent examiners blinded to the tooth type and thickness conducted the measurements.

Incident laser power was measured at the beginning and end of each wavelength group without the tooth sample. To measure transmitted power, light was delivered with a fiber-bundle probe which was held perpendicularly over the maximum crown thickness at the cervical third of the enamel surface of the tooth. The sensor of the calibrated Thorlabs power meter was positioned parallel against the dentino-pulpal junctional surface of the crown segment, aligned with the laser beam to determine the transmitted power (Fig. 1).

All measurements were taken twice, averaged, and recorded in agreement by the examiners. The power meter was calibrated for each wavelength and re-zeroed for each measurement. The study was carried out in an enclosed dark room with operators wearing prescribed laser protective eyewear.

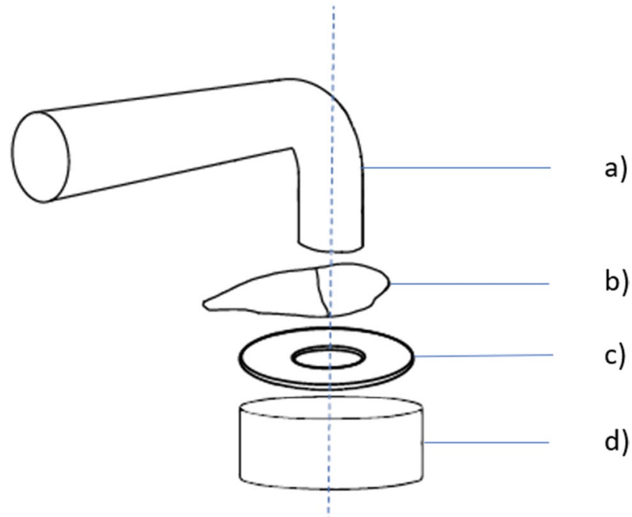

Fig. 1 Schematic representation of the experimental set up with (**a**) fiber-bundle probe, (**b**) sectioned tooth, (**c**) metal washer (internal $\phi = 6$ mm), and (**d**) power meter sensor

Data analysis

The proportion of laser energy delivered to the pulp was determined by converting power measurements to a light transmittance value based on: Light transmittance = Transmitted Power (P_O)/Incident Power (P_I). The line of best fit approximated an exponential relationship better than a linear relation based on curve fitting conducted with SPSS Software. The transmittance values were linearized via log-transformation and a general linear model subsequently used to analyze the effects of wavelengths, teeth type, and thickness on transmittance. Trend lines were used to determine the attenuation value (μ) for each wavelength. Statistical analysis was carried out with SPSS Software. Model assumptions were verified by plotting residuals versus fitted values and versus each covariate in the model. Residuals were also assessed for normal distribution. A value of $P < 0.05$ was selected as the level of significance.

Table 1 Parameters of all experimental wavelengths

Wavelength	450 nm[1]	650 nm[1]	810 nm[2]	980 nm[1]
Mode	Continuous wave	Continuous wave	Continuous wave	Continuous wave
Diameter (cm)	0.80	0.80	0.80	0.80
Area (cm^2)	0.50	0.50	0.50	0.50
Average power (W)	0.50	0.50	0.50	0.50
Power density (W/cm^2)	1.0	1.0	1.0	1.0
Time (s)	10	10	10	10
Energy (J)	5.0	5.0	5.0	5.0
Total energy fluence delivered (J/cm^2)	9.98	9.98	9.98	9.98

[1]Medical Diode Laser Model: S1, Pioon Technology Co. Ltd., Wuhan, China.

[2]D-Touch, Light Instruments Ltd., Yokneam, Israel.

Results

Transmittance ranged from 2 to 18% (± 0.2%) for those samples exposed to 980-nm laser, from 2 to 19% (± 0.2%) in the 810 nm group, from < 0.1 to 10% (± 0.1%) in the 650 nm group, and from < 0.1 to 5% (± 0.5%) in the 450 nm group. One sample (1 anterior) in the 650 nm group and 11 samples (2 anterior, 2 premolars, and 7 molars) in the 450 nm group were not included in the analysis as the transmittance recording was not measurable (less than 0.1mW at the power meter). Tooth thickness ranged from 2.00 to 5.38 mm (± 0.6%). The distribution of tooth thickness and mean transmittance is presented in Table 2.

Factors affecting laser light delivery to the pulp

Tooth thickness and wavelength were predictors of the quantity of light energy delivered to the pulp ($P < 0.05$). Tooth type significantly affected light delivery only for the 450-nm wavelength ($P < 0.05$).

Wavelength

Transmittance varied significantly ($P < 0.001$) between all wavelengths except for a marginally significant difference between 810 and 980 nm ($P = 0.052$). The transmittance of the 980-nm wavelength was approximately 2.0 (95% confidence interval (CI): 1.6, 2.4) times the transmittance of the 650-nm wavelength and 8.4 (95% CI: 6.5, 10.8) times the transmittance of the 450-nm wavelength. Meanwhile, the transmittance of 810-nm wavelength was approximately 2.4 (95% CI: 1.9, 3.0) times the transmittance of the 650-nm wavelength and 10.4 (95% CI: 8.1, 13.5) times the transmittance of the 450-nm wavelength.

The attenuation coefficient for each wavelength is displayed in Table 3.

Table 3 Attenuation coefficient for each wavelength

Wavelength (nm)	Attenuation coefficient (μ) (cm^{-1})	Percentage error (%)
980	2.55	±10
810	2.45	±10
650	1.87	±10
450	5.42	±10

Thickness

Tooth thickness was a significant predictor across all four wavelengths (980: F value (F) = 64.2, $P < 0.001$; 810: $F = 70.5$, $P < 0.001$; 650: $F = 45.8$, $P < 0.001$; 450: $F = 11.5$, $P < 0.005$) (Fig. 2). Transmission decreased exponentially with increasing tooth thickness.

Tooth type

In combined analysis, there was significantly lower transmittance in premolars compared to molars ($P < 0.01$) and anterior teeth ($P < 0.05$). No significant difference between molars and anterior teeth ($P = 0.45$) was observed. However, once each wavelength was analyzed separately (Fig. 2), tooth type was not significantly related to transmittance in the 980 nm ($F = 0.896$, $P = 0.420$), 810 nm ($F = 2.734$, $P = 0.084$), and 650 nm ($F = 2.403$, $P = 0.111$) groups while it was significant in 450 nm group ($F = 5.549$, $P < 0.05$). Premolars had a significantly lower transmittance compared to anterior teeth ($P < 0.01$) in the 450 nm group.

Discussion

To the best of our knowledge, this is the first report which has quantified the light energy from 450-nm, 650-nm, 810-nm, and 980-nm lasers delivered through the cervical dental crown to the pulp chamber. The light delivery to the pulp chamber was significantly mediated by wavelength and tooth

Table 2 Tooth thickness and laser transmittance

Tooth thickness (mm)	*n*	450 transmittance (%) Mean (SD)	650 transmittance (%) Mean (SD)	810 transmittance (%) Mean (SD)	980 transmittance (%) Mean (SD)
2.00–2.49	4	3.81 (0.91)	7.30 (2.30)	16.89 (1.68)	15.03 (2.22)
2.50–2.99	9	1.10 (0.83)	4.59 (1.15)	13.30 (2.99)	9.94 (2.63)
3.00–3.49	4	0.94 (1.33)	2.73 (0.68)	7.66 (0.69)	6.83 (1.00)
3.50–3.99	5	0.22 (0.23)	2.42 (1.53)	5.82 (2.28)	5.20 (1.98)
> 4.00	8	< 0.01 (0.00)	1.92 (0.45)	4.22 (0.88)	3.13 (0.69)

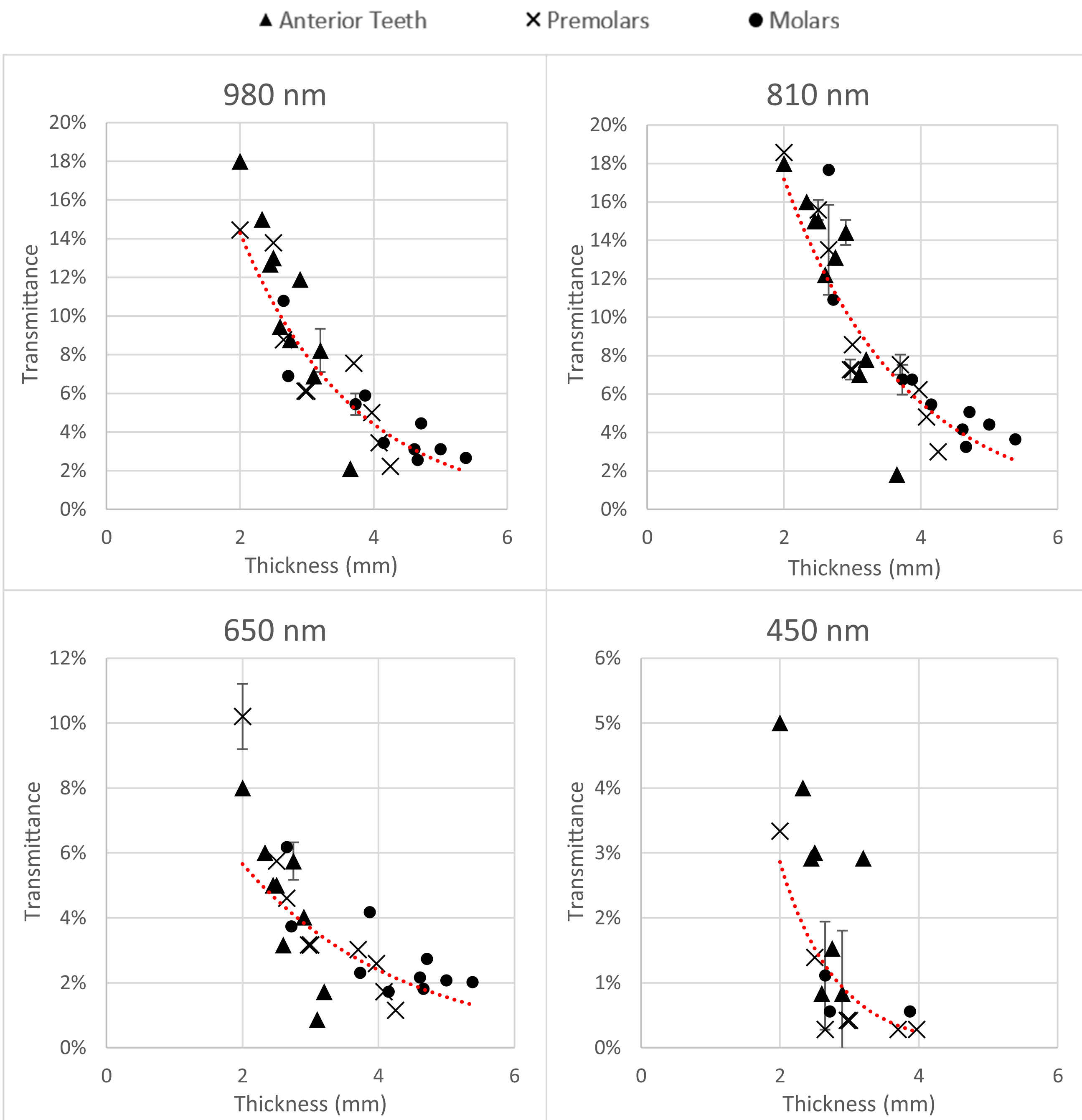

Fig. 2 Scatter plot of each laser wavelength showing the relationships between transmittance (%), thickness (mm), and different tooth types (see legend). The red dotted line indicates the exponential line-of-best-fit. Error bars represent the minimum–maximum range. Transmittance uncertainties less than 0.5% and all thickness uncertainties were not plotted as they were indistinguishable on the graph. 980 nm: $R^2 = 0.76$; 810 nm: $R^2 = 0.74$; 650 nm: $R^2 = 0.66$; 450 nm: $R^2 = 0.64$

thickness with weak evidence suggesting tooth type may have a role.

Our results followed the trends of previous studies which have examined the transmittance of other wavelengths. Watanabe et al. [29, 30] analyzing the wavelengths of 632.8 nm and 830 nm through the cervical-crown, and Chan et al. [28] investigating the wavelengths of 660 nm and 810 nm through the mid-crown, also found that transmitted light delivered to the dentino-pulpal junction decreased with increasing tooth thickness. The reported measurements of previous studies were also comparable. For a 3.5-mm-thick sample, the mean transmittance was 1.26%, 2.0%, and

2.4–2.7%, when irradiated by 632-nm, 660-nm, and 650-nm wavelengths, respectively.

Our study identified an exponential dependence between transmittance, thickness (ℓ), and the attenuation coefficient (μ), given by the equation:

$$Transmittance = Po/P_I = exp(-\mu\ell)$$

There a number of limitations when applying this equation and this may explain our uncertainties (± 10%). It assumes plane wave irradiation, with a homogenous transmission medium, in contrast with real tooth structures [31]. Notwithstanding, this model can be integrated into clinical practice (instead of more complicated models such as the Kubelka–Munk Theory which assumes a one-dimensional isotropic sample, or Monte Carlo Simulations [32]).

Our derived attenuation coefficient values were comparable with the absorption and scattering coefficients obtained from existing spectral measurements. Our μ values were consistent with the reported absorption coefficients of enamel ($\mu_a < 1$ cm^{-1}; $\lambda = 400$–700 nm) [19] and dentine ($\mu_a = 3$–4 cm^{-1}; $\lambda = 543$, 632, 1053 nm) [18]. Attenuation, however, also includes scattering due to hydroxyapatite crystals in enamel and dentinal tubules in dentine [33]. Measurements of dentine and enamel scattering coefficients vary significantly depending on the method; dentine: $\mu_s = 10$–25 cm^{-1} ($\lambda = 400$–700 nm) [22] to 30–200 cm^{-1} ($\lambda = 400$–700 nm) [26]; enamel: $\mu_s = 15$–105 cm^{-1} ($\lambda = 543$, 632, 1053 nm) [18] to 20–400 cm^{-1} ($\lambda = 400$–700 nm) [19]. These values have been derived from thin sections (< 2 mm); therefore, optical effects such as the magnification in dentine tubules caused by multiple scattering may not be accurately represented [34].

Moreover, attenuation was significantly higher for the blue wavelength compared to the other wavelengths. This contrasts with a recent study using standardized 4-mm-thick molar occlusal sections, which found no difference between attenuation for blue, green and red wavelengths ($\mu = 1.95$ cm^{-1}; $\lambda = 405$, 532, 650 nm) [25]. However, our results are consistent with spectral data which demonstrate higher dentine absorption values for shorter wavelengths ($\lambda < 500$ nm) [20, 21], explained by the absorption peaks of organic components within intratubular dentine [22]. The consistent finding that enamel and dentine scattering decreases with increasing wavelength also supports our observation [18, 19, 26].

Our investigations provide weak evidence that tooth types may impact optical transmittance. A significant difference was observed solely in the 450 nm wavelength group; however, this may be related to the substantial proportion of non-measurable samples. Previous laser research consistently reported significantly higher transmittance through anterior teeth compared to posterior teeth with no difference between premolar and molar teeth [28–30]. On the other hand, Pop-Ciutrila et al. [22] using spectro-photometric and spectro-radiometric measurements found that dentine of anterior teeth had lower transmittance than molars. Notably, however, they compared the buccal sections of anterior teeth with occlusal sections of molars.

The unresolved optical differences between teeth types may also be influenced by sampling. In our study, molars were prevailingly wisdom teeth obtained from young adults, premolars from orthodontic patients, and anterior teeth collected from periodontitis patients. This posits external validity implications as teeth sourced from older patients would have more wear-related and age-related dentine sclerosis, in which there is gradual occlusion of dentine tubules by mineral deposition [35, 36]. This narrowing and increased mineralization attenuates light propagation along the tubules [34, 37].

The present study has several strengths including the use of multiple blinded examiners, suitable storage of samples [38], and a rigorous protocol. Standardizing the direction of the incident beam was critical as both enamel and dentine have anisotropic light propagation. Enamel is more translucent when the light path is oriented parallel due to the ordered array of inorganic hydroxyapatite rods and surrounding organic matrix [33, 39]. In dentine, incident light which is propagating parallel along the tubules experiences a smaller refractive index and shorter optical path length [34]. Controlling the irradiation site was also important as dentinal tubules vary in diameter, density, and orientation according to location [40].

Some potential limitations should also be mentioned. Firstly, the dental crown surfaces, including buccal surfaces, have a degree of curvature. Therefore, measurements of maximum tooth thickness may overestimate the average thickness of the tooth structure exposed to the laser beam. Moreover, the fractional composition of enamel and dentine which constituted the measured tooth thickness was not distinguished. While this is important to acknowledge, our study design aimed to simulate clinical applications where laser irradiation is performed on a curved tooth surface and the proportion of enamel and dentine penetrated is unknown.

Our data leave open the possibility that other tooth-related factors play a role, such as tooth color, or the salivary pellicle. The color of a tooth is determined by the volumetric scattering of light and the resulting absorption along this scattering path [41]. Although no tooth in the sample was overtly discolored or stained, small differences in natural tooth color create differences in optical properties. This may affect transmittance for lasers at visible wavelengths. We must also be cognizant that teeth in vivo are covered by the salivary pellicle and biofilm, with unknown implications. To date, no studies have investigated how these layers may affect laser transmittance.

Quantifying the light penetration of four laser wavelengths through the dental crown has clinical implications. Firstly, our results are consistent with existing research that the 450-nm wavelength transmits poorly through tooth structure [21]. This may be advantageous, as the low transmittance diminishes inadvertent irradiation such as during soft tissue procedures, whereas high scattering facilitates efficient curing of composite resins [3]. Secondly, our results demonstrate the promising potential of 980-nm, 810-nm, and 650-nm wavelengths for therapeutic photobiomodulation applications to the pulp. While the higher transmittance of 980-nm and 810-nm lasers would be suitable for thicker teeth, selecting the appropriate wavelength must consider the desired therapeutic targets and biological effects. For instance, the primary mitochondrial chromophore, cytochrome C oxidase, which is suggested to be responsible for a range of therapeutic functions, absorbs wavelengths between 600 and 810 nm [42]. Different molecules, such as light-activated transient receptor potential vanilloid-1 (TRPV-1), absorb higher wavelengths (980–1064 nm) to cause cellular effects [43]. This distinction is critical as growing evidence suggests that specific mechanisms are correlated with specific therapeutic benefits [44].

In order to utilize the full potential of lasers, the chair-side delivery must be accurate. This study identified a consistent discrepancy between the selected power output on the laser unit display and the actual output as recorded by the calibrated power meter. While this was accounted for in calculating the energy delivery, this is an important reminder; both to users to frequently calibrate laser units prior to use, and to manufacturers to continue advancing technology such as in-built power meters or monitoring systems which support the precise delivery of laser parameters.

Overall, the tabulated values provided in this study should be interpreted with awareness of the significant variation between person to person, tooth to tooth, and the same tooth at different times or locations [45]. Quantifying the light energy to the pulp contributes to a better recognition of the tissue-specific optical properties. This enables heuristic and eventually precise anticipation of the impact that clinical variations will have at any desired treatment wavelength. For example, tooth thickness and pulp chamber location, as derived from radiographs, can customize and optimize the light delivery. Further studies might consider other tooth-related factors affecting laser energy delivery, such as tooth orientation and different laser polarizations.

Conclusion

Our findings quantify for the first time to our knowledge the energy delivery of 450 nm, 650 nm, 810 nm, and 980 nm wavelength lasers through dental hard tissue to the pulp chamber, to inform the appropriate design of clinical laser treatment for photobiologic effects. Evaluating the effect of tooth thickness and potentially other tooth-related factors on optical transmittance will facilitate the focused design of future research. These measurements lay foundations for more reliable clinical dental treatments with lasers.

Author contribution All authors contributed to conceptualisation and methodology. Formal analysis and first draft was prepared by Alex Simon Chan. Review and editing was performed by all authors. All authors read and approved the final manuscript.

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Declarations

Ethics approval Approval was obtained from the Human Research Ethics Committee of University of Sydney, NSW, Australia (Project Number: 2021/421).

Conflict of interest The authors declare no competing interests.

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