

The Effect of Beam Direction on Absorption and Transmission of Ultraviolet to Infrared Wavelength Regions in Three Different Dentin Thicknesses



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Abstract

Introduction: Lasers and optics have been used extensively in dental procedures in recent years, and realizing the optical properties of the tooth is also an essential in its successful applications. The aim of this study was to compare the absorption and transmission of applied wavelengths in the range of 190–1100 nm at different dentin thicknesses and the effect of changing the direction of radiation emission on the dentin tubules.

Methods: There were fifteen dentin specimens with thicknesses of 300, 600, and 1000 μ m, five specimens for each thickness, prepared through a transverse section of the coronal dentin over the pulpal roof area of human molars. Considering the coronal-apical and apical-coronal directions, we measured the absorption and transmission of parallel light rays perpendicular to the dentin samples in different thicknesses and two directions with a Cecil CE 7400 UV/Vis spectrometer. Data analysis was performed using SPSS software version 19. P value < 0.05 was considered significant.

Results: The absorption rate of the ultraviolet wavelength range was significantly higher than that of visible and infrared light irradiation from both directions at three thicknesses ($P < 0.001$). The radiation shift direction had no significant differences in the absorption and transmission of wavelengths of ultraviolet, visible, and infrared light in any of the three thicknesses ($P > 0.05$).

Conclusion: Accordingly, attenuation or transmission losses of light in the ultraviolet to infrared range clearly depend on the wavelength of light and the optical properties of dental dentin, and the thickness of the dentin used in this study has a little effect.

Keywords: Spectrometer; Transmission losses; Optical beam.



Introduction

Understanding the optical properties of dentin is considered necessary in various fields of odontology. The domain of these effects is important from a diagnostic, clinical and cosmetic point of view as color matching plays a key role.¹⁻³ Furthermore, the effects of laser light on the mechanisms of cavity preparation and dentin surface treatment^{4,5} as well as the disinfection process⁶ and various dimensions of tissue regeneration are evident.^{7,8} These effects are currently well-used, and the applications of lasers and LEDs in various treatments of different areas of dentistry have received remarkable attention and proved to be highly efficient.⁹⁻¹²

Lasers are used in endodontic treatments to assist in decay removal, to access cavity preparation, and to treat the dentin surface in the canal to remove the smear layer. In addition, they are widely used and have been shown

to be effective in disinfecting root canals and dentinal tubules.^{13,14} In addition to the areas mentioned above, the use of lasers to stimulate cells in studies on tissue and cell regeneration has also gained importance in recent years.¹⁵⁻¹⁷ The use of lasers in the range of blue light to infrared light in the root canals leads to various effects on dentinal tissue, including a photothermal disinfection effect,^{18,19} a developmental stimulation of the healing process for the surrounding tissue in the alveolus,^{17,20} and the activation of the irrigation solutions in the canal.²¹ Therefore, it has been proposed as an important tool for disinfecting root canals and dentinal microtubules in endodontics.^{21,22} On the other hand, the morphology of the dentinal tubules and the geometric pattern of their orientation are also important for light distribution and propagation.²³⁻²⁵ In many cosmetic treatments and bleaching processes^{26,27} as well as in the treatment

of dentine hypersensitivity,^{28,29} the pattern of the laser beams runs from the outside of the dentine to its inside. When light enters biological tissues, a combination of absorption, transmission, reflection, and scattering occurs, and considering the anisotropic nature of these tissues, the optical properties and patterns of light distribution in these tissues are fundamentally dependent on the patterns of elements, and tissue microstructures responsible for the light source are relevant.^{25,30,31} Dentinal tubules exhibit hyper-mineralization in the pretubular wall, which could alter the absorption pattern and beam distribution due to the conical shape of these dentinal microstructures.^{32,33}

The estimation of beam absorption in dentin or other tissue is a function of the frequency and wavelength of that light.³⁴⁻³⁶ However, a few studies have investigated the patterns of laser beam absorption in dentin, in particular the depth of penetration and its effect on the absorption amount and distribution.^{23,31,37} Considering the gap in the literature, the present researchers aimed to investigate the absorption scale and transmission of beams and the effect of changing the direction of beam emission on dentinal tubules in the range of ultraviolet light and infrared light, which is carried out via the spectroscopy absorption method in three thicknesses of 300, 600 and 1000 μm as dentin slices.

Materials and Methods

In this experimental laboratory study, the population consisted of extracted molars due to periodontal problems. According to Table 1, in Otsuki and colleagues' study²³ with 90% power, 95% confidence, and 70% drop (since the discs are fragile and the probability of rupture is very high in the experiment), The maximum sample size obtained was five in each group.

After receiving approval code IR.GOUMS.REC.1398.212 from the Golestan University of Medical Sciences Ethics Committee, 15 molars without cracks, defects or morphological changes that were periodontally hopeless were extracted and collected.

Teeth were first cleaned and kept in 2.5% sodium hypochlorite solution for disinfection for 15 minutes,

rinsed with double distilled water, and kept in 0.5% chloramine-T solution until the beginning of the study.^{38,39}

Then, for more similarity in the orientation of the dentine tubules, the sample preparation had to be made in the three thicknesses of 300, 600 and 1000 μm perpendicular to the longitudinal axis of the tooth in the upper area of the pulp chamber. Therefore, considering the sample size, we placed five samples in each group. A water-cooled diamond blade was used to cut each molar on a precision cutting machine (Mecatome, Presi, France) to obtain cross-sections of these thicknesses. To do this, we first inserted the teeth into a transparent plastic block. Then the block was cut in parallel in the desired increments. After that, we first used 10 mL of EDTA 17% (PULPDENT, Watertown, MA, USA) with a syringe to irrigate each sample for one minute and then with 10 mL of NaOCl 5% for 1 minute each to remove the smear layer and finally the samples washed with 10mL of distilled water to remove any of the deposits.⁴⁰

Taking into account the conical structure of the dentine tubules, we applied the light irradiation in the coronal and apico-coronal directions to analyze the optics from both radiation directions of the samples (Figure 1), so preservation and transfer of the sample direction were carried out very carefully, and their direction was marked on the slide.

During the irradiation, we fixed the samples between two Plexiglas slides with a gap of 5 mm width and 2.5 cm length in the middle. This slit is in front of the light source where the sample is placed in the spectrometer holder. This design is essential to remove interfering factors such as slide thickness to pass a beam of light through the slit and direct radiation onto the sample. Therefore, by changing the direction of placing the sample holder in the holder spectrometer, it is possible to study the effect of this change in the direction of the tubules on the amount of attenuation or the lost amount of transmitted light (Figure 2).

Changes in the beam source can lead to unavoidable behavior in the parameters of geometric measurements, and absorption determination can be accompanied by justifiable errors.

Table 1. Comparison of Absorption and Transmission in the Corono-apical Beam Direction of Ultraviolet, Visible, and Infrared Wavelength Regions at Each Thickness

Thickness	Variable	Mean \pm Standard Deviation			F	P Value
		Ultraviolet (1)	Visible Light (2)	Infra-Red (3)		
300 μm	Absorption	1.38 \pm 0.37 ^A	0.64 \pm 0.16 ^B	0.62 \pm 0.17 ^B	14.56	0.001
	Transmission	10.07 \pm 5.08 ^A	24.41 \pm 10.19 ^A	23.28 \pm 11.30 ^A	2.80	0.100
600 μm	Absorption	1.76 \pm 0.32 ^A	0.65 \pm 0.12 ^B	0.61 \pm 0.11 ^B	47.13	<0.001
	Transmission	10.20 \pm 3.46 ^A	24.18 \pm 7.25 ^B	22.02 \pm 6.49 ^B	7.94	0.006
1000 μm	Absorption	1.55 \pm 0.23 ^A	0.60 \pm 0.10 ^B	0.56 \pm 0.10 ^B	47.71	<0.001
	Transmission	10.14 \pm 3.95 ^A	24.82 \pm 5.34 ^B	22.18 \pm 5.21 ^B	10.29	0.005

Two-way analysis of variance and the Tukey's post hoc tests ($P < 0.05$). Different superscripts of the capital letters in each row represent a statistical difference.

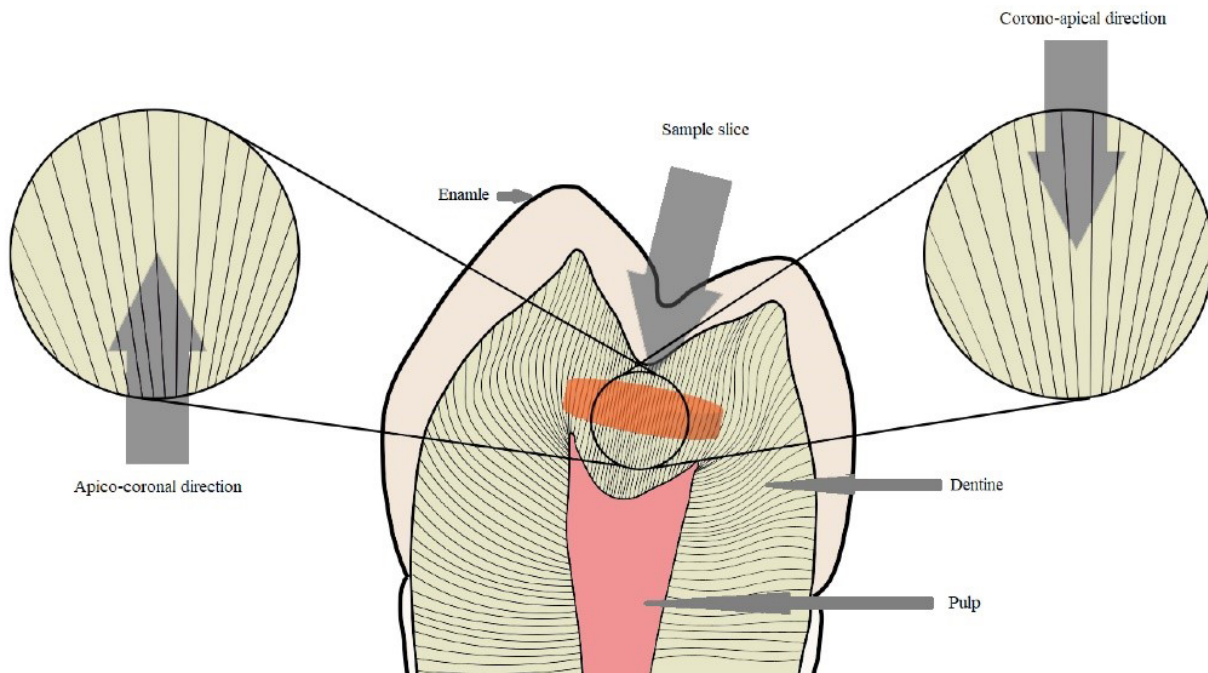


Figure 1. Schematic Representation of a Human Molar Dentine Disc Showing the Prepared Tubular Course and Both Directions of Beam Irradiation

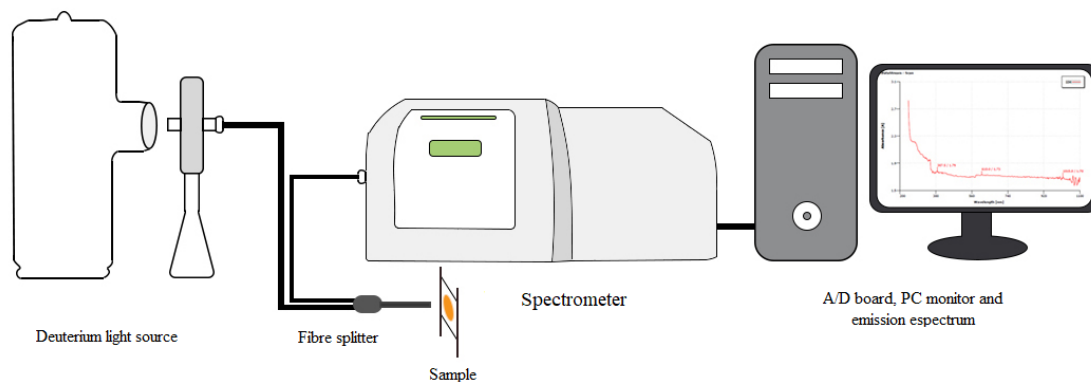


Figure 2. Schematic Illustration of the Experimental Set-up Used in the Measurement of the Absorption and Transmittance on the Dentinal Disks

However, the fact that the amount of absorption depends on the wavelength is important, and it is recommended in experiments conducted to determine the absorption of biological tissue using beam sources with a continuous radiation scale.³³ For this reason, the present study used a double beam Cecil CE 7400 UV/VISIBLE, Cecil instrument limited, England spectrometer device to examine beam absorption. This spectrometer employs an emission spectrum within a 190-to-1100-nm wavelength as a source of light and is able to measure the transmission and absorption curves with high accuracy and speed for liquid and narrow solid samples within this wavelength spectrum. Light perpendicular to the objects is directed at a fixed distance, and immediately upon the experimented samples, the transmitted ray is directed to the spectrometer of the device. After measuring the absorption/transmission spectrum for the samples, the

amount of beam absorption/transmission at specified wavelengths (within the UV range: at two wavelengths of 220 and 255 nm; within the invisible light range: at wavelengths of 445, 515, 632.5, and 660 nm; and within the IR range: at wavelengths of 810, 940, 980, and 1065 nm) can be extracted from the absorption/transmission spectra to determine the changes in beam absorption/transmission depending on the thickness of the samples. Absorption might be exhibited as transmittance, $T=I/I_0$, or absorbance, $A=\log I_0/I$, where I and I_0 represent the intensities of the transmitted and incident light respectively. Thus, absorbance and transmittance are dimensionless.

Moreover, it is possible to study the effect of changing the direction of the incident beam in the thickness of dentin discs on the amount of beam absorption by the device and its standard algorithm. Hence, we placed each

sample from both directions in the device holder so that the samples received the radiation beam in both apico-coronal and coronal-apical directions.

Statistical Analysis

Analyses were performed using the SPSS software program (IBM SPSS Statistics 19, SPSS Inc., Somers, NY, USA). The normality of the data was verified by the Kolmogorov-Smirnov test.

The two-way ANOVA was used for comparing the mean values between the tested groups, and also Tukey's post hoc test was used for pair-wise comparison, where the level of significance was set at $P < 0.05$. Finally, the independent-samples *t* test was used to compare the direction of radiation in the amount of absorption and transmission among the study groups.

Results

According to Table 1, the spectrometer extracted the mean and standard deviation of the absorption and transmission rate in the wavelengths of ultraviolet, visible, and infrared regions in three thicknesses of 300, 600, and 1000 microns. The normality of the data was confirmed by the Kolmogorov-Smirnov test, and the two-way analysis of the Fisher test showed that there was a significant difference in the absorption and transmission

of ultraviolet, visible, and infrared wavelength regions emitted from above by these three thicknesses ($P < 0.001$), and in two-way comparisons with the Tukey's post hoc test, the absorption of the ultraviolet wavelength was found to be greater than the visible and infrared wavelengths in all three thicknesses, and in the ultraviolet wavelength region, specimens with a thickness of 600 microns had the highest absorption in dentin. There was also no significant difference between the absorption and transmission of visible and infrared light at three thicknesses ($P > 0.05$). The lowest transmission was in the UV wavelength range at 1000 μm .

Figures 3 and 4 also show further details of the measurement. Figure 3 shows the UV-Vis absorbance spectra for a typical sample series (600 μm thickness) in the apico-coronal and coronal-apical incident beam directions. The average absorbance and transmittance spectra are shown in Figure 4 for all samples in both incident directions.

As Table 2 shows, at these three thicknesses there is a significant difference ($P < 0.001$) in the amount of absorption and transmission of ultraviolet, visible and infra-red light wavelengths emitted from the apico-coronal direction. There is no significant difference in the transmission of visible and infrared light wavelengths ($P > 0.05$). Infrared and visible light wavelengths at a

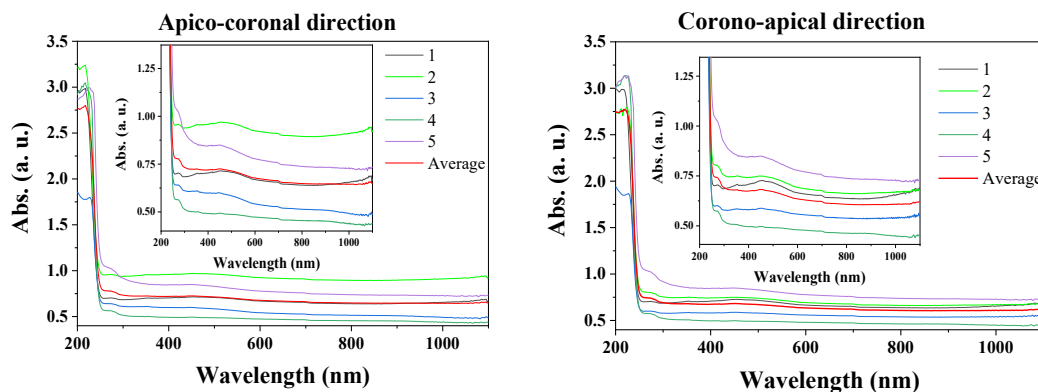


Figure 3. Absorption of Light Irradiation of Dentin Samples With 600 μm Thickness in Both Apico-coronal and Corono-apical Incident Beam Directions. Insets show the magnified portion of the spectra

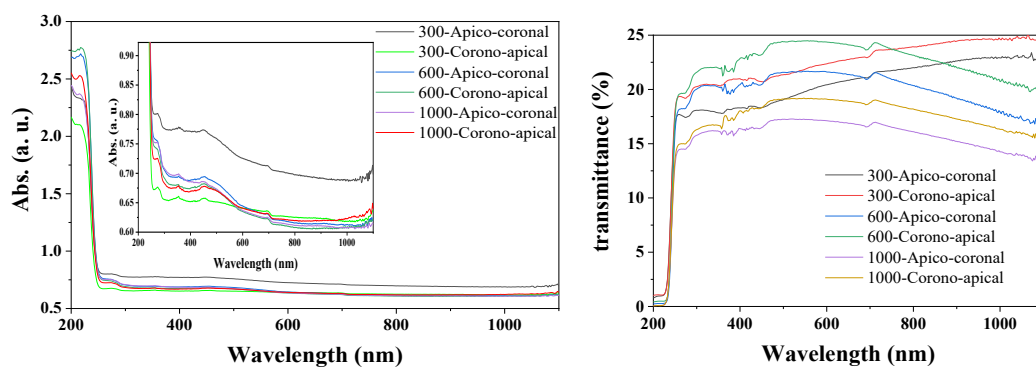


Figure 4. Absorption and Transmission Spectra of Dentin Samples With 300, 600 and 1000 μm Thicknesses in Both Apico-coronal and Corono-apical Incident Beam Directions. Inset shows the magnified portion of the spectra

thickness of 600 μm have the lowest absorption, and ultraviolet wavelength regions at a thickness of 1000 μm have the lowest transmission of dentin.

In addition, according to the results of Table 3, an independent-samples t-test showed that the irradiance shift direction in the amount of absorption and transmission of ultraviolet, visible and infrared wavelength regions was not significant in all three thicknesses and could be considered statistically ineffective ($P > 0.05$).

Finally, Figure 5 demonstrates further details about the difference in absorption and transmission between the three wavelengths of ultraviolet, visible light and infrared in three dentin thicknesses.

Discussion

The aim of the study was to compare the absorption and transmission of light radiation in the ultraviolet to infrared wavelength range in three dentine thicknesses.

This experimental laboratory study with a descriptive analytic approach was performed on 15 dentin samples with thicknesses of 300, 600 and 1000 μm and five samples from each thickness. Ultraviolet, visible and infrared wavelength regions were irradiated from above (corono-apical) and below (apico-coronal). The penetration of light radiation through dentin samples depends on the optical properties of the tissue, chromophores such as pigments, hydroxyapatite and water, the technical specifications of the device, and the operation method.^{37,41}

Changes in the beam source can lead to unavoidable behavior in the parameters of geometric measurements, and absorption determination can be accompanied by justifiable errors.

However, the fact that the amount of absorption depends on the wavelength is important, and it is recommended in experiments conducted to determine the absorption of biological tissue using beam sources with a continuous

Table 2. Comparison of Absorption and Transmission in the Apico-coronal Beam Direction of Ultraviolet, Visible, and Infrared Wavelength Regions at Each Thickness

Thickness	Variable	Mean \pm Standard Deviation			F	P Value
		Ultraviolet (1)	Visible Light (2)	Infra-Red (3)		
300 μm	Absorption	1.58 \pm 0.37 ^A	0.74 \pm 0.26 ^B	0.69 \pm 0.27 ^B	13.23	0.001
	Transmission	9.27 \pm 4.71 ^A	20.08 \pm 9.78 ^A	23.39 \pm 11.61 ^A	3.23	0.075
600 μm	Absorption	1.73 \pm 0.30 ^A	0.66 \pm 0.14 ^B	0.60 \pm 0.13 ^B	45.64	<0.001
	Transmission	10.16 \pm 3.93 ^A	20.23 \pm 6.74 ^B	18.07 \pm 5.67 ^B	6.33	0.013
1000 μm	Absorption	1.49 \pm 0.26 ^A	0.63 \pm 0.12 ^B	0.57 \pm 0.14 ^B	28.41	<0.001
	Transmission	8.66 \pm 3.44 ^A	23.41 \pm 6.12 ^B	20.78 \pm 6.48 ^B	6.20	0.020

Two-way analysis of variance and the Tukey's post hoc tests ($P < 0.05$). Different superscripts of the capital letters in each row represent a statistical difference.

Table 3. Comparison of the Change in the Radiation Direction to the Rate of Absorption or Transmission of Ultraviolet, Red Visible, and Infrared Wavelength Regions

Thickness	Wavelength	Variable	Mean \pm Standard Deviation		F	P Value
			Coronol-apical	Apico-coronal		
300 μm	Ultraviolet	Absorption	1.38 \pm 0.37	1.58 \pm 0.37	0.84	0.42
		Transmission	10.07 \pm 5.08	9.27 \pm 4.71	0.26	0.80
	Visible light	Absorption	0.64 \pm 0.16	0.74 \pm 0.26	0.71	0.49
		Transmission	24.41 \pm 10.19	20.08 \pm 9.78	0.35	0.95
	Infra-red	Absorption	0.62 \pm 0.17	0.69 \pm 0.27	0.49	0.63
		Transmission	23.28 \pm 11.30	23.39 \pm 11.61	0.31	0.98
600 μm	Ultraviolet	Absorption	1.76 \pm 0.32	1.73 \pm 0.30	0.07	0.90
		Transmission	10.20 \pm 3.46	8.66 \pm 3.44	0.71	0.49
	Visible light	Absorption	0.45 \pm 0.12	0.47 \pm 0.11	0.62	0.78
		Transmission	24.18 \pm 7.25	20.23 \pm 6.74	0.42	0.68
	Infra-red	Absorption	0.61 \pm 0.11	0.60 \pm 0.13	0.03	0.86
		Transmission	22.02 \pm 6.49	18.07 \pm 5.67	0.45	0.66
1000 μm	Ultraviolet	Absorption	1.55 \pm 0.23	1.49 \pm 0.26	0.05	0.90
		Transmission	10.14 \pm 3.95	8.66 \pm 3.44	0.55	0.59
	Visible light	Absorption	0.60 \pm 0.10	0.63 \pm 0.12	0.44	0.40
		Transmission	24.82 \pm 5.34	23.41 \pm 6.12	0.23	0.82
	Infra-red	Absorption	0.56 \pm 0.10	0.57 \pm 0.14	0.11	0.57
		Transmission	22.18 \pm 5.21	20.78 \pm 6.48	0.30	0.76

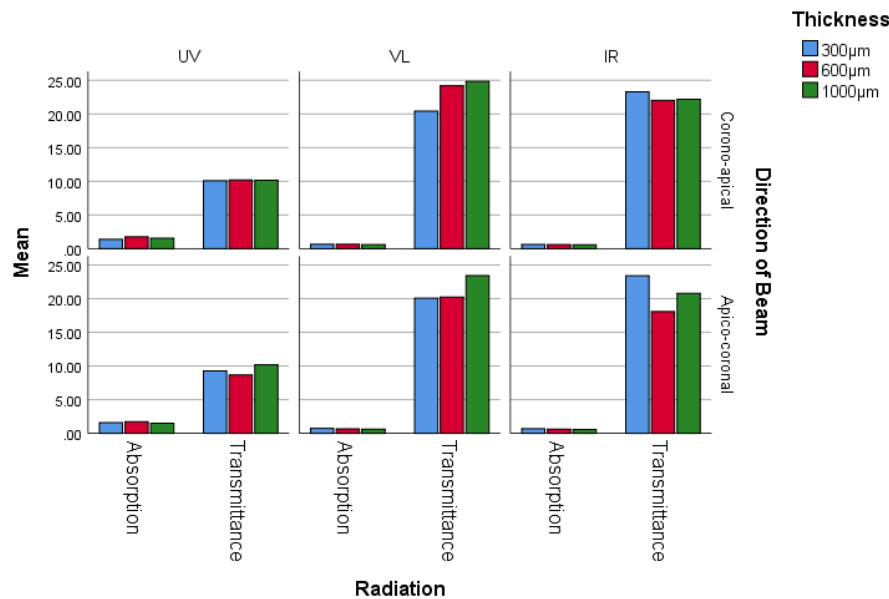


Figure 5. Bar Graph Representing the Rate of Absorption and Transmission in Two Directions of Irradiation

radiation scale.³³ For this reason, a double beam Cecil the CE 7400 UV/VISIBLE spectrometer device was used in this study to examine beam absorption.

Gutknecht et al investigated the antibacterial effect of a blue 445-nm diode laser on *Enterococcus faecalis* in root canal dentin in human teeth at three thicknesses of 300, 500 and 1000 µm and showed the effectiveness of a blue diode laser at the corresponding radiation parameters.¹⁹ For this reason, we used three dentin thicknesses to study the measurement of absorbance and light transmission in the above wavelength regions.

Dogandzhiyska et al³⁷ measured the absorption and penetration of light in the wavelength range of 350-1000 nm on dentin samples of 1-mm thickness prepared from above the roof of the pulp chamber perpendicular to the long axis of the tooth. They reported that the highest tissue uptake of radiation was observed in the blue spectral range and the lowest in the infrared spectral range. The lower the absorption of light of a certain wavelength by the dentine was, the greater its transmission would be. In contrast, in our study, dentin samples with three different thicknesses of 300, 600 and 1000 µm were used in a broader light spectrum from 190 to 1100 nm. The specimens were only cut across the roof of the ventricular pulp perpendicular to the long axis of the tooth for more matching. Nevertheless, our study showed that the transmittance and absorbance of the ultraviolet wavelength region spectrum was significantly different for visible and infrared light wavelengths ($P > 0.001$).

In addition, some studies have evaluated the optical properties of light scattering through dentin and enamel. Zijp and Bosch⁴² used a theoretical model to irradiate 16 µm thin layers of dentin, which were cut parallel to the tubules, with He-Ne laser light at different angles in

order to determine the light transmission in the vertical and parallel directions to the dentin tubules. They concluded that dentinal tubules are directly involved in light scattering on this tissue. When light was irradiated parallel to the dentinal tubule, the transmission of the dentin was more intense. On the other hand, light perpendicular to the axis of the dentinal tubules further reduced its intensity (related to the anisotropic properties of dentin). These data suggest that the transcendental transmission of laser light occurs at least in part through dentinal tubules.

Otsuki et al conducted a study entitled "Transmission and passage of laser light through dentin" using a laser with a wavelength of 805 ± 20 nm and on one-millimeter dentin slices, one half was prepared perpendicular to the long axis of the tooth and the other half parallel to it. The study found that the laser beam transmission in sections perpendicular to the dentinal tubules was two and a half times higher than in sections prepared parallel to the tubules.²³ In another study by Vaarkamp et al, various sections were prepared, and they examined 15 enamel samples and 15 dentin samples with parallel and perpendicular sections of the proximal teeth with a thickness of about 0.03-0.85 mm and light transmission using a He-Ne laser light source (633 nm) by changing the angle of radiation. Their study demonstrated the ability to transmit light through dentinal tubules with a high refractive index based on internal reflection through peritubular dentin.⁴³

In this study, to simulate the clinical irradiation conditions during dental treatments such as endodontics and bleaching, the rays were irradiated in both corono-apical and apico-coronal directions due to inconsistencies in the existing dentinal tubules. However, the thickness of

the slices might partially affect the anisotropic properties of the samples, so dentine slices with thicknesses of 0.3, 0.6 and 1 mm were used. However, the results could not be directly attributed to the findings obtained by irradiating dentin slices from the proximal area of the teeth or thicker dentin slices.^{42,43}

Generally, a spectrometer provides a reading of the extinction coefficient (total light loss) as a measure of signal strength versus a reference signal. This attenuation is due to the absorption and scattering of light in the matter.² One of the shortcomings of this study is the lack of scatter measurement; however, the thin thickness of the samples and the low attenuation coefficient of dentin could partially compensate for this shortcoming. Berghammer et al showed that no significant difference was found between the attenuation coefficients of sound dentin. Although this attenuation in the ultraviolet range appeared to be fundamentally different from the longer wavelength, they attributed this result to the number and density of dentinal tubules as the main source of light scattering.⁴⁴

In our study, two factors are considered important to justify the weaker association between dentin permeability and light attenuation and distribution. First, the dentin slices were cut from the upper part of the pulp chamber, and the opening of the dentin tubules was wider at this distance. The second and most important factor relates to the direction of radiation, which was along the dentinal tubules from coronal-apical or apico-coronal sides.

The results of this study showed that the irradiation protocol used, based on which the irradiation angle and dentine cross-section were adjusted from one sample to another, did not affect transdentinal light transmission. There is a possibility that the transient difference in the tubule number and diameter could affect light transmission, but no study to date has reported the significant impact of these factors on light distribution through the structure of dentin. Therefore, it could be assumed that the number and diameter of the tubes might help the light distribution, although this might not be statistically significant. For this reason, there was no direct correlation between dentin permeability and the attenuation of transdentinal light.

Furthermore, it seems important to wash the surface of the dentin with EDTA prior to the permeability experiment because the open openings of the tubules facilitate light transmission. A smear layer consisting of mineral debris resulting from cutting and rinsing could reduce 86% of dentin permeability.⁴⁵

In another study, Kienle et al³⁰ provided dentine slices of 1-3 mm thickness from the upper part of the pulp chamber. In addition, they studied He-Ne laser light transmission at a wavelength of 633 nm through intertubular dentin, which consisted mainly of collagen fibers and hydroxyapatite crystals. The amount of light

on EDTA cleaned dentin slices was reduced by only 2% (from 61 to 59%) compared to the slices covered with a smear layer. This result shows that under the experimental conditions and parameters of LEDs, the presence of a smear layer per se does not play a notable role in reducing transdentinal light transmission.

In the present study, despite the removal of the smear layer that had formed on both sides (pulpal and occlusal) of the disc, light attenuation was not affected when changing the direction of radiation, indicating the ability of light distribution through the dentinal tubules.

Conclusion

According to the results of this study, the amount of beam absorption and the transmission of infrared and visible light wavelengths were the same for the three thicknesses of 300, 600 and 1000 mm. The ultraviolet wavelength region had the lowest transmission and the highest absorption in dentin, and this was statistically significant. Although changing the direction of radiation may not lead to significant differences in the amount of transmission and absorption at ultraviolet, visible light and infrared wavelength regions for the three thicknesses, this could be clinically important due to the diversity of treatment protocols; therefore, further studies need to be conducted.

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Author Contributions

EE and EK wrote the main manuscript text, and EK also prepared figures. HKF extracted the data, figures and described their analysis. AK analyzed the statistics and wrote the Results section of the article.

Conflict of Interests

The authors declare that they have no conflict of interest.

Ethical Considerations

This study was approved by the Ethics Committee of Golestan University of Medical Sciences (Ethics No. IR.GOUMS.REC.1398.212).

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References

1. Chandler NP, Pitt Ford TR, Monteith BD. Laser light passage through restored and carious posterior teeth. *J Oral Rehabil.* 2014;41(8):630-4. doi: [10.1111/joor.12173](https://doi.org/10.1111/joor.12173).
2. Hoffmann L, Feraric M, Hoster E, Litzenburger F, Kunzelmann KH. Investigations of the optical properties of enamel and dentin for early caries detection. *Clin Oral Investig.* 2021;25(3):1281-9. doi: [10.1007/s00784-020-03434-x](https://doi.org/10.1007/s00784-020-03434-x).
3. Lee YK. Translucency of human teeth and dental restorative materials and its clinical relevance. *J Biomed Opt.* 2015;20(4):045002. doi: [10.1117/1.jbo.20.4.045002](https://doi.org/10.1117/1.jbo.20.4.045002).

4. Li T, Zhang X, Shi H, Ma Z, Lv B, Xie M. Er:YAG laser application in caries removal and cavity preparation in children: a meta-analysis. *Lasers Med Sci.* 2019;34(2):273-80. doi: [10.1007/s10103-018-2582-x](https://doi.org/10.1007/s10103-018-2582-x).
5. Guidotti R, Merigo E, Fornaini C, Rocca JP, Medioni E, Vescovi P. Er:YAG 2,940-nm laser fiber in endodontic treatment: a help in removing smear layer. *Lasers Med Sci.* 2014;29(1):69-75. doi: [10.1007/s10103-012-1217-x](https://doi.org/10.1007/s10103-012-1217-x).
6. Olivi M, Raponi G, Palaia G, Berlutti F, Olivi G, Valentini E, et al. Disinfection of root canals with laser-activated irrigation, photoactivated disinfection, and combined laser techniques: an ex vivo preliminary study. *Photobiomodul Photomed Laser Surg.* 2021;39(1):62-9. doi: [10.1089/photob.2020.4879](https://doi.org/10.1089/photob.2020.4879).
7. Shivakoti I, Kibria G, Cep R, Pradhan BB, Sharma A. Laser surface texturing for biomedical applications: a review. *Coatings.* 2021;11(2):124. doi: [10.3390/coatings11020124](https://doi.org/10.3390/coatings11020124).
8. Sin JH, Walsh LJ, Figueredo CM, George R. Evaluation of effectiveness of photosensitizers used in laser endodontics disinfection: a systematic review. *Transl Biophotonics.* 2021;3(1):e202000007. doi: [10.1002/tbio.202000007](https://doi.org/10.1002/tbio.202000007).
9. Gupta S, Kumar S. Lasers in dentistry-an overview. *Trends Biomater Artif Organs.* 2011;25(3):119-23.
10. Morsy DA, Negm M, Diab A, Ahmed G. Postoperative pain and antibacterial effect of 980 nm diode laser versus conventional endodontic treatment in necrotic teeth with chronic periapical lesions: a randomized controlled trial. *F1000Res.* 2018;7:1795. doi: [10.12688/f1000research.16794.1](https://doi.org/10.12688/f1000research.16794.1).
11. Convissar RA, Ross G. Photobiomodulation lasers in dentistry. *Semin Orthod.* 2020;26(2):102-6. doi: [10.1053/j.sodo.2020.06.005](https://doi.org/10.1053/j.sodo.2020.06.005).
12. Mylona V, Anagnostaki E, Parker S, Cronshaw M, Lynch E, Grootveld M. Laser-assisted aPDT protocols in randomized controlled clinical trials in dentistry: a systematic review. *Dent J (Basel).* 2020;8(3):1207. doi: [10.3390/dj8030107](https://doi.org/10.3390/dj8030107).
13. Schulte-Lünzum R, Gutknecht N, Conrads G, Franzen R. The impact of a 940 nm diode laser with radial firing tip and bare end fiber tip on *Enterococcus faecalis* in the root canal wall dentin of bovine teeth: an in vitro study. *Photomed Laser Surg.* 2017;35(7):357-63. doi: [10.1089/pho.2016.4249](https://doi.org/10.1089/pho.2016.4249).
14. Nasher R, Hilgers RD, Gutknecht N. Debris and smear layer removal in curved root canals using the dual wavelength Er,Cr:YSGG/diode 940 nm laser and the XP-endoshaper and finisher technique. *Photobiomodul Photomed Laser Surg.* 2020;38(3):174-80. doi: [10.1089/photob.2019.4693](https://doi.org/10.1089/photob.2019.4693).
15. Ferreira LS, Diniz IMA, Maranduba CMS, Miyagi SP, Rodrigues M, Moura-Netto C, et al. Short-term evaluation of photobiomodulation therapy on the proliferation and undifferentiated status of dental pulp stem cells. *Lasers Med Sci.* 2019;34(4):659-66. doi: [10.1007/s10103-018-2637-z](https://doi.org/10.1007/s10103-018-2637-z).
16. Kulkarni S, Meer M, George R. Efficacy of photobiomodulation on accelerating bone healing after tooth extraction: a systematic review. *Lasers Med Sci.* 2019;34(4):685-92. doi: [10.1007/s10103-018-2641-3](https://doi.org/10.1007/s10103-018-2641-3).
17. Alves FA, Marques MM, Cavalcanti S, Pedroni AC, Ferraz EP, Miniello TG, et al. Photobiomodulation as adjunctive therapy for guided bone regeneration. A microCT study in osteoporotic rat model. *J Photochem Photobiol B.* 2020;213:112053. doi: [10.1016/j.jphotobiol.2020.112053](https://doi.org/10.1016/j.jphotobiol.2020.112053).
18. Katalinić I, Budimir A, Bošnjak Z, Jakovljević S, Anić I. The photo-activated and photo-thermal effect of the 445/970 nm diode laser on the mixed biofilm inside root canals of human teeth in vitro: a pilot study. *Photodiagnosis Photodyn Ther.* 2019;26:277-83. doi: [10.1016/j.pdpdt.2019.04.014](https://doi.org/10.1016/j.pdpdt.2019.04.014).
19. Gutknecht N, Al Hassan N, Martins MR, Conrads G, Franzen R. Bactericidal effect of 445-nm blue diode laser in the root canal dentin on *Enterococcus faecalis* of human teeth. *Lasers Dent Sci.* 2018;2(4):247-54. doi: [10.1007/s41547-018-0044-1](https://doi.org/10.1007/s41547-018-0044-1).
20. Kim HK, Kim JH, Abbas AA, Kim DO, Park SJ, Chung JY, et al. Red light of 647 nm enhances osteogenic differentiation in mesenchymal stem cells. *Lasers Med Sci.* 2009;24(2):214-22. doi: [10.1007/s10103-008-0550-6](https://doi.org/10.1007/s10103-008-0550-6).
21. Bago I, Plečko V, Gabrić Pandurić D, Schauerperl Z, Baraba A, Anić I. Antimicrobial efficacy of a high-power diode laser, photo-activated disinfection, conventional and sonic activated irrigation during root canal treatment. *Int Endod J.* 2013;46(4):339-47. doi: [10.1111/j.1365-2591.2012.02120.x](https://doi.org/10.1111/j.1365-2591.2012.02120.x).
22. Lukač N, Jezeršek M. Amplification of pressure waves in laser-assisted endodontics with synchronized delivery of Er:YAG laser pulses. *Lasers Med Sci.* 2018;33(4):823-33. doi: [10.1007/s10103-017-2435-z](https://doi.org/10.1007/s10103-017-2435-z).
23. Otsuki M, Kijima M, Tagami J. Transmission of diode laser through dentin. *J Jpn Soc Laser Dent.* 2010;21:18-21. doi: [10.5984/jjpsoclaserdent.21.18](https://doi.org/10.5984/jjpsoclaserdent.21.18).
24. Nakajima M, Arimoto A, Prasansuttiporn T, Thanatvarakorn O, Foxton RM, Tagami J. Light transmission characteristics of dentine and resin composites with different thickness. *J Dent.* 2012;40 Suppl 2:e77-82. doi: [10.1016/j.jdent.2012.08.016](https://doi.org/10.1016/j.jdent.2012.08.016).
25. Hariri I, Sadr A, Shimada Y, Tagami J, Sumi Y. Effects of structural orientation of enamel and dentine on light attenuation and local refractive index: an optical coherence tomography study. *J Dent.* 2012;40(5):387-96. doi: [10.1016/j.jdent.2012.01.017](https://doi.org/10.1016/j.jdent.2012.01.017).
26. Surmelioglu D, Usumez A. Effectiveness of different laser-assisted in-office bleaching techniques: 1-year follow-up. *Photobiomodul Photomed Laser Surg.* 2020;38(10):632-9. doi: [10.1089/photob.2019.4741](https://doi.org/10.1089/photob.2019.4741).
27. Méndez Romero JM, Villasanti Torales UA, Villalba Martínez CJ. Efficacy of laser application in dental bleaching: a randomized clinical controlled trial. *Am J Dent.* 2020;33(2):79-82.
28. Chen CL, Parolia A, Pau A, Celerino de Moraes Porto IC. Comparative evaluation of the effectiveness of desensitizing agents in dentine tubule occlusion using scanning electron microscopy. *Aust Dent J.* 2015;60(1):65-72. doi: [10.1111/adj.12275](https://doi.org/10.1111/adj.12275).
29. Moeintaghavi A, Ahrari F, Nasrabadi N, Fallahrestegar A, Sarabadani J, Rajabian F. Low level laser therapy, Er,Cr:YSGG laser and fluoride varnish for treatment of dentin hypersensitivity after periodontal surgery: a randomized clinical trial. *Lasers Med Sci.* 2021;36(9):1949-56. doi: [10.1007/s10103-021-03310-4](https://doi.org/10.1007/s10103-021-03310-4).
30. Kienle A, Michels R, Hibst R. Magnification--a new look at a long-known optical property of dentin. *J Dent Res.* 2006;85(10):955-9. doi: [10.1177/154405910608501017](https://doi.org/10.1177/154405910608501017).
31. Uusitalo E, Varrelä J, Lassila L, Vallittu PK. Transmission of Curing light through moist, air-dried, and EDTA treated dentine and enamel. *Biomed Res Int.* 2016;2016:5713962. doi: [10.1155/2016/5713962](https://doi.org/10.1155/2016/5713962).
32. Chandler NP, Pitt Ford TR, Watson TF. Pattern of transmission of laser light through carious molar teeth. *Int Endod J.* 2001;34(7):526-32. doi: [10.1046/j.1365-2591.2001.00428.x](https://doi.org/10.1046/j.1365-2591.2001.00428.x).
33. Odor TM, Chandler NP, Watson TF, Ford TR, McDonald F. Laser light transmission in teeth: a study of the patterns in different species. *Int Endod J.* 1999;32(4):296-302. doi: [10.1046/j.1365-2591.1999.00224.x](https://doi.org/10.1046/j.1365-2591.1999.00224.x).
34. Schmid FX. Biological Macromolecules: UV-Visible Spectrophotometry. 2001. <https://www.life.illinois.edu/biochem/455/Lab%20exercises/2Photometry/spectrophotometry.pdf>.
35. Roberts J, Power A, Chapman J, Chandra S, Cozzolino D. The use of UV-Vis spectroscopy in bioprocess and fermentation

- monitoring. *Fermentation*. 2018;4(1):18. doi: [10.3390/fermentation4010018](https://doi.org/10.3390/fermentation4010018).
36. Mohd Zain MN, Yusof ZM, Yazid F, Ashari A, Wong KS, Lee WJ, et al. Absorption spectrum analysis of dentine sialophosphoprotein (DSPP) in orthodontic patient. *AIP Conf Proc*. 2020;2203(1):020007. doi: [10.1063/1.5142099](https://doi.org/10.1063/1.5142099).
37. Dogandzhiyska V, Angelov I, Dimitrov S, Uzunov TS. In vitro study of light radiation penetration through dentin, according to the wavelength. *Acta Med Bulg*. 2015;42(2):16-22. doi: [10.1515/amb-2015-0013](https://doi.org/10.1515/amb-2015-0013).
38. Titley KC, Chernecky R, Rossouw PE, Kulkarni GV. The effect of various storage methods and media on shear-bond strengths of dental composite resin to bovine dentine. *Arch Oral Biol*. 1998;43(4):305-11. doi: [10.1016/s0003-9969\(97\)00112-x](https://doi.org/10.1016/s0003-9969(97)00112-x).
39. Mobarak EH, El-Badrawy W, Pashley DH, Jamjoom H. Effect of pretest storage conditions of extracted teeth on their dentin bond strengths. *J Prosthet Dent*. 2010;104(2):92-7. doi: [10.1016/s0022-3913\(10\)60098-4](https://doi.org/10.1016/s0022-3913(10)60098-4).
40. Darda S, Madria K, Jamenis R, Heda A, Khanna A, Sardar L. An in-vitro evaluation of effect of EDTAC on root dentin with respect to time. *J Int Oral Health*. 2014;6(2):22-7.
41. Tunér J, Hode L. *The New Laser Therapy Handbook: A Guide for Research Scientists, Doctors, Dentists, Veterinarians and Other Interested Parties Within the Medical Field*. Grängesberg: Prima Books; 2010.
42. Zijp JR, Bosch JJ. Theoretical model for the scattering of light by dentin and comparison with measurements. *Appl Opt*. 1993;32(4):411-5. doi: [10.1364/ao.32.000411](https://doi.org/10.1364/ao.32.000411).
43. Vaarkamp J, ten Bosch JJ, Verdonchot EH. Propagation of light through human dental enamel and dentine. *Caries Res*. 1995;29(1):8-13. doi: [10.1159/000262033](https://doi.org/10.1159/000262033).
44. Berghammer K, Litzeburger F, Heck K, Kunzelmann KH. Attenuation of near-ultraviolet, visible and near-infrared light in sound and carious human enamel and dentin. *Clin Oral Investig*. 2022;26(9):5847-55. doi: [10.1007/s00784-022-04541-7](https://doi.org/10.1007/s00784-022-04541-7).
45. Marijnissen JPA, Star WM. Quantitative light dosimetry in vitro and in vivo. *Lasers Med Sci*. 1987;2(4):235-42. doi: [10.1007/bf02594166](https://doi.org/10.1007/bf02594166).