



Characterization and effectiveness of a violet LED light for in-office whitening

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Abstract

Objectives This study characterized a violet LED light (V-LED; bright max whitening) tooth whitening device and evaluated its efficacy on stained enamel compared to hydrogen peroxide (HP).

Materials and methods Characterization of the V-LED beam profile was performed using a laser beam-profiler. The irradiance was measured throughout an exposure cycle at 0- and 8-mm distances using an integrating sphere and a spectral radiometer. Bovine enamel/dentin blocks stained with black tea (BT), cigarette smoke (CS), or without staining (CONT) were subjected to V-LED or 40% HP ($n = 10/\text{group}$). Color parameters (ΔL , Δa , Δb , and ΔE_{00}) were measured using a digital spectrophotometer. Light transmission was estimated through 1-mm-thick bovine enamel slices ($n = 5$). ΔL , Δb , ΔE_{00} , and irradiance were analyzed by two-way ANOVAs and Tukey's tests, Δa by Kruskal–Wallis and Mann–Whitney tests, and light transmission by t -test ($\alpha = 5\%$).

Results Heterogeneous beam distribution was observed for the emitting V-LED chips. After 20 sequential exposures, irradiance levels were reduced 25–50%, regardless of the distance from V-LED. Localized irradiance values were statistically different between beam locations and different distances from the target. V-LED produced lower ΔE_{00} , ΔL , Δa , and Δb values than HP for CONT and BT, with no differences for CS. Light transmittance decreased approximately 98% through 1-mm thick enamel.

Conclusions V-LED irradiance was heterogeneous and decreased throughout the exposure cycles and was also greatly reduced with increasing tip distance. V-LED produced a significantly lower whitening effect on BT and control teeth.

Clinical relevance This study contributes to the knowledge of V-LED and its clinical use.

Keywords Tooth bleaching · Dental enamel · Violet LED light · Irradiance · Staining

Introduction

Light-assisted, chair-side tooth whitening is a technique often used by dentists, and several light devices are available designed to enhance whitening results [1]. However, recent evidence implies that neither halogen lights nor blue LEDs enhance the final outcome of whitening when used with hydrogen peroxide (HP) or carbamide peroxide (CP) [2]. In view of this fact, the maintenance of this combination is debatable as negative effects were described in the literature, such as higher intrapulpal HP concentration [3]. Also, the application of whitening gels on enamel is sufficient to cause trans-enamel/dentin penetration of HP into the pulp chamber [4], which has been demonstrated to affect pulpal tissue viability [5]. Moreover, a decrease in microhardness [6], bond strength [7], and an increase in surface roughness

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of enamel [8] promoted by whitening gels were previously reported in vitro. Thus, alternative techniques for decreasing these adverse effects should be investigated in order to improve the safety of vital tooth whitening.

The use of LED technology at a visible violet wavelength for the purpose of whitening teeth in the absence of gels [9] is currently in use. This new generation of LED device presents a curved acrylic tip with light-emitting diodes capable of illuminating all teeth at the same time [10]. Sparse literature is available regarding the effectiveness of this technique; however, recent studies show that violet LED (V-LED) exposure, by itself, promoted whitening or increased the effectiveness of peroxide gels [11–13]. According to some authors, the wavelength of the V-LED (405–410 nm) could correspond to the absorption peak of chromophore molecules in surface stains [12, 14]. Because these molecules are highly reactive, it is speculated that the presence of violet light could trigger instability of the chemical bonds, leading to a breakdown of bonds and promoting the whitening effect by a physical process [15].

Among the reports on the ability of V-LEDs to promote color changes is an evaluation of lessening stains left by black tea [11, 16]. The authors observed that V-LED alone was capable of changing tooth color, but to a lesser extent than HP or CP [11, 16]. The whitening effect of V-LED exposure was hypothesized to be the breakdown of red and yellow polyphenolic chromophores of the tea [16]. Therefore, the ability of the V-LED to whiten may be associated with the type of extrinsic pigment residing on the external dental structure, because it is well-known that violet light has low penetration through enamel [17–19]. Thus, understanding the effect of V-LED light for whitening of different stains adhered to the enamel outer surface would be a primary step in understanding the mechanism of action of this light. In this context, research demonstrates that cigarette smoking results in deposition of chemicals on enamel surfaces [20], which can absorb violet wavelength energy [21]. Thus, evaluating the effectiveness of violet light on cigarette smoke staining, along with the determination of the depth to which violet light can pass through enamel, might clarify the rationale of violet light enamel whitening effectiveness.

Also, the determination of both the irradiance and beam profile characteristics of the V-LED whitening light unit is paramount in determining its interaction with external discoloration. Such analyses have been described for conventional light units [22–24], providing essential information for the quality of resin composites light curing. However, currently, there is no data characterizing V-LED used for tooth whitening and measuring the continuity of irradiance levels throughout the exposure cycle from such a commercial device. In addition, there is no information on the homogeneity of the emitted beam across the device's emitting surface, which could indicate the quality of the light

source and, consequently, its potential for predictable tooth whitening capability.

The purpose of this study was to characterize a commercially available V-LED light designed for vital tooth whitening (Bright Max Whitening, MMOptics, São Carlos, SP, Brazil) and to evaluate the effectiveness of the V-LED to minimize enamel staining produced by cigarette smoke (CS) and black tea (BT), compared to the use of a conventional, commercial hydrogen peroxide agent. Additionally, measurement of the violet light transmitted through enamel was performed. The research hypotheses tested were that (1) the mean irradiance of the V-LED light source would significantly decrease during a recommended exposure interval, or among repeated, sequential exposures; (2) increasing the tip-to-target distance up to 8-mm would result in significantly lower irradiance than the value observed at the emitting end of the V-LED light unit; (3) exposure to the V-LED would provide significantly less whitening effect compared to a conventional HP whitening gel, regardless of the type of enamel staining, and (4) violet light would be significantly attenuated in irradiance by passage through a 1-mm thick enamel section.

Material and methods

Overall experimental design

This study was divided into three phases. The first phase (*Light characterization*) quantified different aspects of the V-LED unit (Bright Max Whitening, MMOptics, São Carlos, SP, Brazil): stability of irradiance during a single exposure cycle and over repeated, sequential exposures, the effect of increasing tip-to-target distance, and the uniformity of irradiance within the V-LED beam profile. The V-LED light was characterized according to the spectral irradiance and total irradiance at the emission end and at 8-mm distance, the capability to provide a consistent irradiance during the exposure time, and the uniformity of emitted beam at the tip end.

The second phase (*Whiteness evaluation*) evaluated colorimetric changes on bovine enamel stained with black tea or cigarette smoke after whitening with the V-LED unit or when using a standard hydrogen peroxide gel, with no additional light treatment. This phase included a total of 60 enamel/dentin blocks of bovine teeth submitted to distinct “staining” protocols ($n=20/\text{protocol}$):

- I. Black tea solution (BT)
- II. Cigarette smoke (CS)
- III. No staining control (CONT)

After staining, specimens were submitted to one of the following “whitening” protocols ($n = 10$ /protocol):

- I. V-LED irradiation (V-LED)
- II. High-concentrated hydrogen peroxide (HP)

Figure 1 illustrates a diagram of the research’s second phase. Color parameters of each tooth prior to and subsequent to whitening procedures were obtained using a handheld spectrophotometer. Color changes as a result of treatment (ΔL , Δa , Δb , ΔE_{00}) were then calculated.

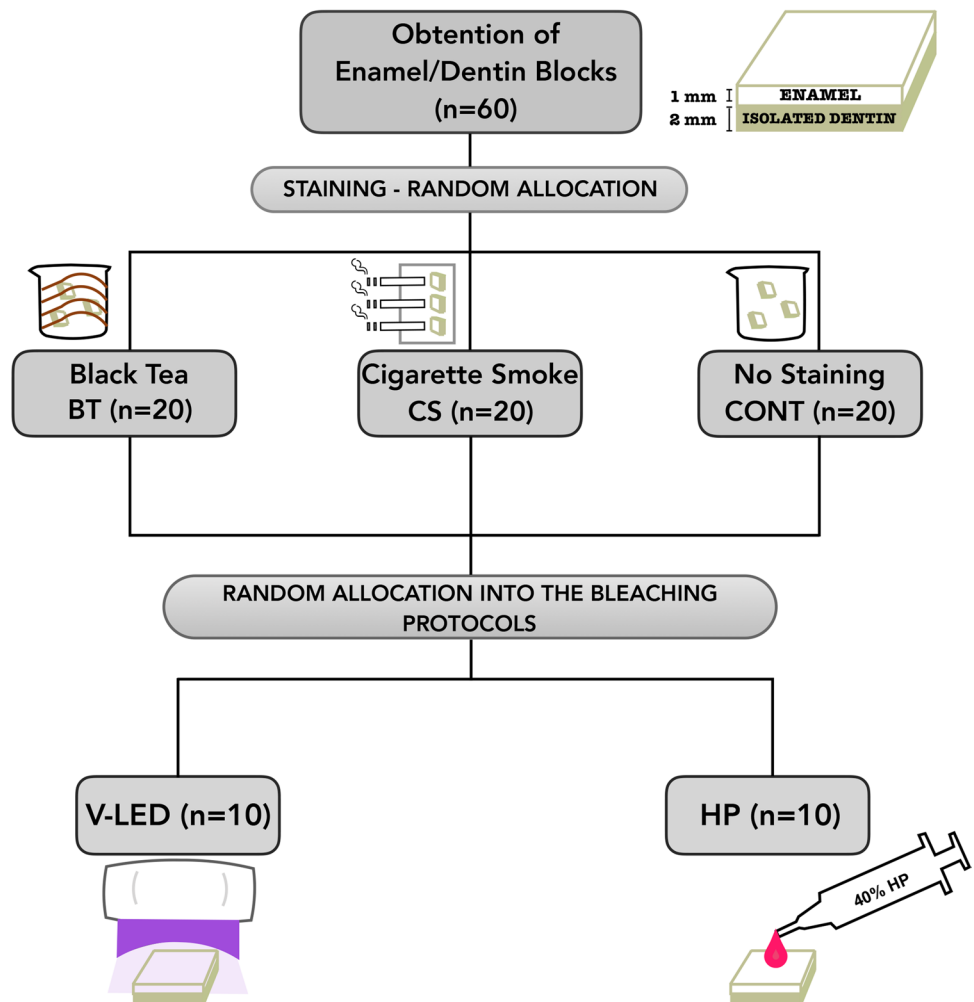
In the third experimental phase (*V-LED light transmission*), the light transmittance of the V-LED wavelength through controlled thicknesses of bovine enamel slices ($n = 5$) was assessed.

Spectral irradiance and beam profiling

The V-LED unit contains 4 LED sources with two emitting chips each. The spectral power of the emitted light was measured using a calibrated 6” integrating sphere

(LabSphere, N. Sutton, NH, USA) and a spectral radiometer (USB 2000+, Ocean Optics, Dunedin, FL, USA). The power distribution profile of the emitted beam at the acrylic surface of the V-LED unit was evaluated using a laser beam-profiler (Model LBA-FW-SCOR20, Spiricon Inc., Logan, UT, USA). First, the beam profile was recorded without a target, and the light distribution across the emitting end was directly visualized. Then, a second beam profile was recorded using a target (a square glass grounded with 1500 grit abraded glass plate [DG2X2-1500, ThorLabs, Newton, NJ, USA]) on one side. The resulting images of the beam profiles were collected using a software (LBA-FW SCOR Software, Spiricon, North Logan), where a rectangular area confined the beam analysis to capture the four emitting LED source emissions. The software used the power measured over this rectangle to calculate the pixel intensities and distributed power levels over the entire emission area. Different scales of irradiance were obtained for profiles with or without the target, in which white and “warm” colors represented high irradiance values in comparison to “cold” colors, representing lower irradiance levels.

Fig. 1 Diagram illustrating the second phase of the research (whiteness evaluation)



Violet LED irradiance and change in output during an exposure cycle

The irradiance of the V-LED was determined using a spectral radiometer (USB 2000+, Ocean Optics, Dunedin, FL, USA), attached to an integrating sphere (CTSM-LSM-60-SF, Labsphere Inc., N. Sutton, NH, USA) and specific software (Spectra Suit STVS-VIS, Ocean Optics). The spectral irradiance accuracy of this system had been calibrated using methods traceable to NIST. The spectral irradiance profile, as well as the total irradiance, were measured at 0-mm distance from the radiometer located at the spot corresponding to the position of the right upper central incisor (RT). Measurement at this location ($n=3$) was used to determine the optimal irradiance of the device during the V-LED whitening protocol recommended by the manufacturer, consisting of twenty sequential 1-min exposures interrupted by 30 s intervals of no exposure, for a total of 30 min. Next, to simulate the clinical application (Fig. 2A to C), the tip of the V-LED was positioned at the manufacturer-recommended maximum distance of 8-mm from the target (integrating sphere aperture), and the same irradiation cycle was performed.

Additionally, irradiance was measured at two distinct locations, which simulated the location in the upper arch of RT and left central (LT) incisors at 0-mm and 8-mm distance from the radiometer. The 8-mm distance was applied because this is recommended by the V-LED's manufacturer when performing the whitening sessions in the patients. These measurements were repeated five times ($n=5$), but only at the beginning of the V-LED irradiation cycle. The RT and LT spots were determined based on a printed template with the average upper arch's teeth locations. The template was temporarily positioned on the surface of the acrylic tip. The diagram in the Fig. 3 illustrates the use of the template. A mark was made in the middle of RT and LT locations. These exact locations were positioned towards the aperture of the spectral radiometer in order to detect the

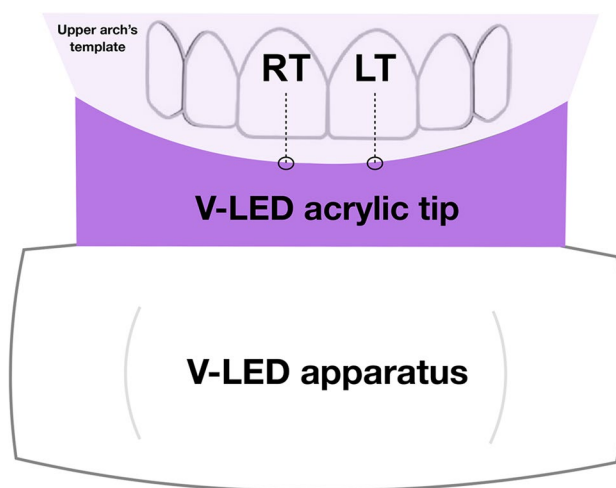


Fig. 3 Diagram representing the method used to determine the location of the acrylic tip corresponding to the point in which the V-LED would irradiate the right (RT) and left (LT) upper central incisors. The template was removed, and these marked locations were positioned towards the aperture of the spectral radiometer at a 0 or 8-mm distance. In this manner, the profile of power distributed to these two tooth locations was measured

corresponding irradiance, at a 0- or 8-mm distance from the aperture.

Specimen preparation

Anterior bovine teeth were collected and stored in 0.1% thymol solution for no longer than one month. Teeth were cleaned using a periodontal scaler and were submitted to air abrasion using sodium bicarbonate to remove extrinsic staining. Sixty blocks of enamel/dentin (each enamel outer surface = 25 mm²) were obtained from the buccal surfaces by sectioning the crowns with a water-lubricated diamond saw (Isomet-Buehler, Lake Bluff, IL, EUA). The blocks were fixed in an acrylic holder with the enamel surface positioned downwards and the dentin surface,



Fig. 2 Images of the V-LED light device: (A) the unit presents a curved acrylic tip coupled with the device's body. (B) The position of the light-emitting tip end held against the maxillary anterior arch of a dentiform model, note the manufacturer-recommended maximum

tooth-to-tip distance is 8-mm. (C) Same image as in panel "B," but with the V-LED turned on, illuminating all anterior teeth at the same time

upwards. Then, the free surface of dentin of each block was abraded with a sandpaper (#600, Norton, Guarulhos, SP, Brazil) using a rotary polisher (Arotec, Cotia, SP, Brazil) under copious irrigation until the thickness of dentin reached 2 mm. The final thickness of the dental blocks was checked with a digital caliper (Mitutoyo Co., Kanagawa, Japan). The thickness of each block was equal to 3.0 mm (Enamel = 1.0 mm; Dentin = 2.0 mm). One third of the blocks remained unstained (the experimental control) and were stored in freshly prepared artificial saliva [1.5 mM calcium (CaCl₂), 0.9 mM phosphate (NaH₂PO₄), 0.15 mM KCl, pH 7.0] [25, 26]. The solution was renewed every two days. The remaining teeth were submitted to black tea or cigarette smoke staining, as described below.

Staining protocols

The dentin surfaces of the dental blocks were isolated using nail polish to prevent contact with the stain. For BT staining, two grams of black tea (Leão, São Paulo, SP, Brazil) were placed into boiling water (100 mL). Five minutes after infusion, the tea was cooled to room temperature (22 °C). Thus, only the enamel portions of the blocks ($n = 20$) were exposed to the tea, placed in the black tea solution for 24 h [27] and stirred every 4 h. Following the 24 h-immersion, the stained blocks were rinsed in deionized water, sonicated in deionized water for 5 min, and stored in artificial saliva at 37 °C up to the beginning of whitening protocols.

An additional set of dental blocks ($n = 20$), used for CS staining, were fixed in utility wax in an acrylic holder leaving only the enamel surface exposed. This holder was placed in a machine that simulates smoking that was developed by the Operative Dentistry Division, Department of Restorative Dentistry, Piracicaba Dental School-UNICAMP (No. 01810012043 INPI, National Institute of Industrial Property). The machine simulates the smoking behavior usually performed by a smoker, with the smoke remaining in contact with specimens for 3 s. The mechanism consists of inhaling

the atmospheric air every 10 s, and the smoke produced is kept in contact with the enamel surface of the specimen, followed by exhalation. The blocks were submitted to one pack of cigarettes (Marlboro, Philip Morris Brazil, Santa Cruz do Sul, RS, Brazil) a day for five consecutive days [28]. Between cycles of exposure, and upon completion of the total treatment, the specimens were stored in the artificial saliva, similarly to the tea-stained blocks.

Whitening protocols and colorimetric evaluation of tooth surfaces

The dental blocks were subdivided ($n = 10$ /treatment group) and submitted to either exposure to the V-LED or HP-whitening treatment. Twenty 1-min exposures to the V-LED were performed, allowing a 30 s non-exposed interval between exposures [26]. A total of 8 sessions were performed on each treated block. The buccal enamel surfaces of the blocks were firmly positioned upward and 8 mm distant from the V-LED acrylic tip. Specimens were rehydrated continuously by using moist gauze during the intervals. Figure 2 illustrates the shape of the V-LED acrylic tip as well as its ideal position towards teeth. The illuminated area comprises a wide reach of the light of both upper and lower arches, as it is possible to observe in the picture using a dentiform. The HP group was treated with a 40% HP gel (0.1 g, Opalescence Boost, Ultradent, South Jordan, UT, USA) applied on the enamel surface for 15 min, rinsed thoroughly, followed by a second application. This procedure was repeated a second time after 72 h. The treated blocks were stored in artificial saliva at room temperature among the sessions.

The colorimetric evaluation of the enamel in each treatment group was performed before (T_0) and after (T_B) the whitening therapies using a digital hand-held spectrophotometer (EasyShade, Vita Zahnfabrik, Bad Säckingen, Germany) with the active point of the device in the center of each specimen. Four repeated measurements were made and the average of the color parameters were recorded (L^* , a^* and b^*) and ΔL , Δa , Δb values were calculated. The color change of enamel (ΔE_{00}) was calculated using the CIEDE2000 system [29], as follows:

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + RT \cdot \left(\frac{\Delta C'}{K_C S_C}\right) \cdot \left(\frac{\Delta H'}{K_H S_H}\right)}$$

Light transmission through enamel

One-mm thick enamel slices ($n = 5$) were obtained from freshly extracted bovine teeth using a diamond saw (Isomet-Buehler, Lake Bluff, IL, EUA). The slices were wet-polished using SiC abrasive polishing paper (#600, #1200 grits) and positioned over a flat, thin holder having a 3.3 mm diameter hole in the middle. The holder was positioned in the center of the integrating sphere previously mentioned, which was connected to the same light-measurement system previously described. A high-power, plasma arc LCU (sn6000, Arc Light II, Air Techniques Inc., Hicksville, NY, USA)

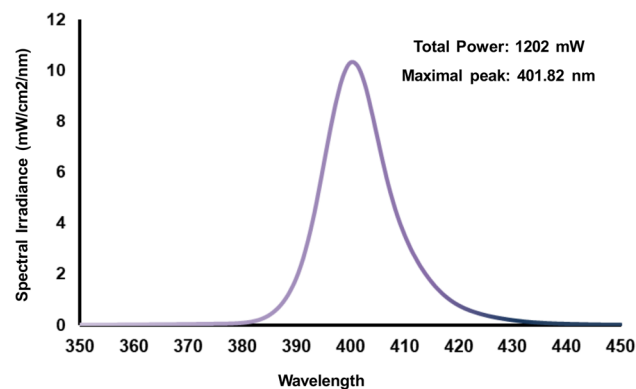


Fig. 4 The spectral distribution of violet light emitted by the V-LED device at a 0-mm distance

was used in this analysis. The tip of the plasma arc light was placed in contact with the 1-mm thick enamel specimen.

Statistical analyses

The data were tested for normality and homoscedasticity using the Shapiro–Wilk and Levene tests ($p > 0.05$), respectively. The ΔL values were transformed into Log_{10} and ΔE_{00} , ΔL , Δb and irradiance (RT and LT central incisor locations) values were evaluated by two-way ANOVA and Tukey post hoc tests. The Δa values were compared using Kruskal–Wallis and Mann–Whitney tests. Light transmission through enamel was analyzed by a Student t -test. The statistical analyses were performed using software (Version 15.0, SPASS, IBM SPSS Inc., Armonk, NY, USA) using a pre-set alpha of 0.05.

Results

Spectral irradiance

The spectral irradiance of the V-LED device is shown in Fig. 4. Irradiance was detected within the violet wavelength range. The maximum peak observed was at 401.82 nm. The total power of the V-LED was 1.202 mW, and the total radiant emittance 137.4 mW/cm².

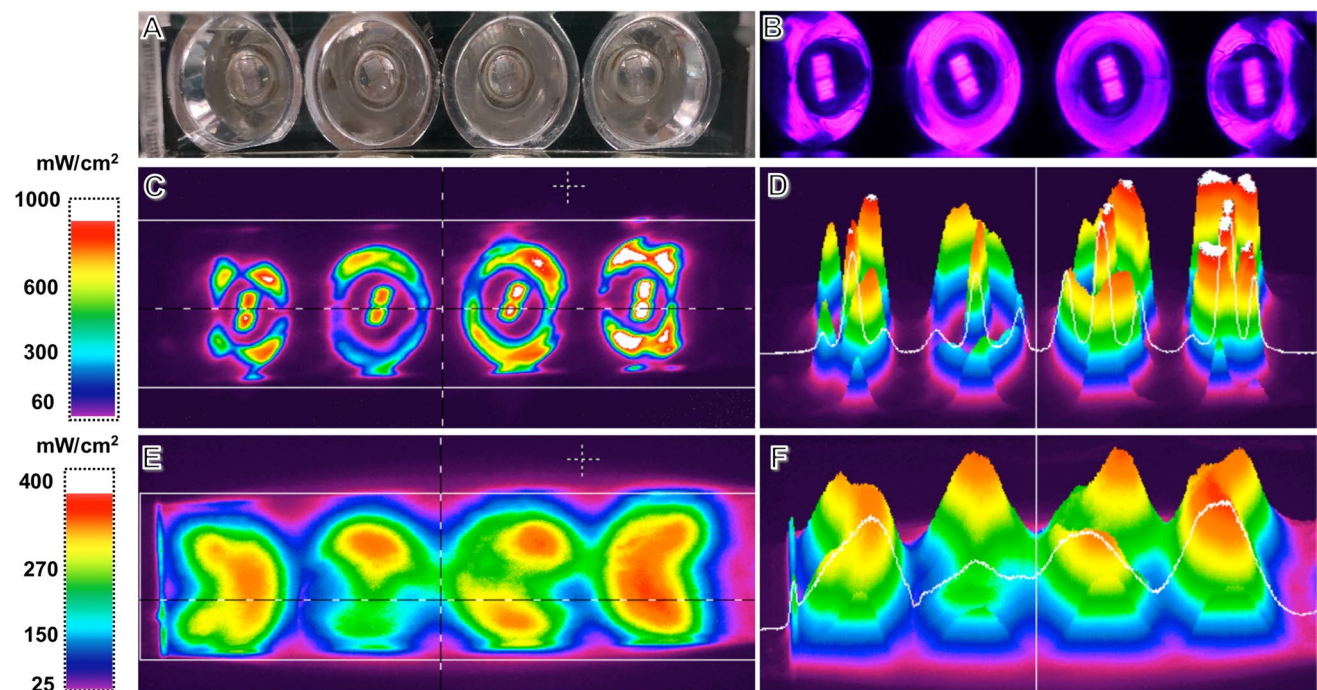


Fig. 5 Images of the V-LED device tip (**A** chips off and **B** chips on) and beam irradiance profiles of the light-emitting diodes of the V-LED light source without (**C** [2-D] and **D** [3-D]) or with (**E** [2-D] and **F** [3-D]) the ground glass target in place

Beam profiling

The power contained within the rectangular beam area was 1.2 watts (1,200 mW). The non-targeted beam profile of the V-LED unit exhibited a very heterogeneous distribution of irradiance from the V-LED chips across the emitting end of the curved acrylic tip. Figure 5 illustrates the distribution of the chips along the acrylic tip, turned off (Fig. 5A) and turned on (Fig. 5B). The location of the chips is observed in the center of each light unit body. Violet light is emitted through the chips, and reflection of this light is seen in the entire peripheral areas (Fig. 5B). The heterogeneity in light output of each chip, especially when the target was not used, is illustrated in Fig. 5C–D. Analysis of the 2-D beam profile revealed that the V-LED chips produce localized spots with high energy represented by red and white colors, presenting irradiance values near 910 mW/cm² (without target, Fig. 5C) and 410 mW/cm² (with a target, Fig. 5E).

It is noteworthy that only the emitting areas of the V-LED chips (peripheral and central regions) exhibit irradiance at least equal to the values noted in the blue areas (~200mW/cm²) or higher (Fig. 5C). The white areas indicate pixel saturation (values greater than ~1000mW/cm²). Moreover, analysis of the 3-D beam profile shows “flat” areas receiving low irradiance, ranging from 110 to 910 mW/cm² (without target, Fig. 5D) and from 110 to 510 mW/cm² (with a target, Fig. 5F). Imaging of the light falling on a target indicated a better distribution of irradiance, because the whole area of the chips presented irradiance compatible with at least the intensity levels of the blue areas (Fig. 5E). However, the presence of a target (Fig. 5E–F) resulted in a lower irradiance, and the presence of higher and “warmer” (higher intensity) locations in certain areas were maintained.

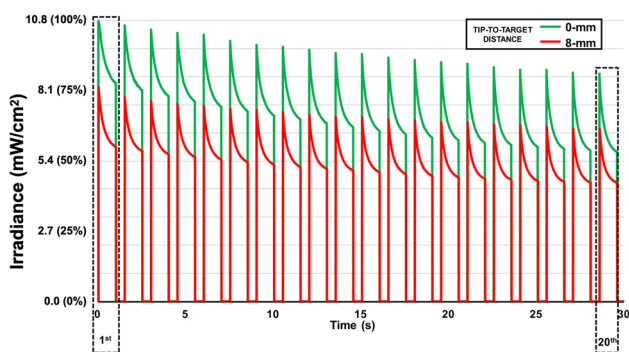


Fig. 6 Irradiance of V-LED light (according to the values described in Table 1) at 0 mm (green line) and 8 mm (red line) tip-to-target distances after a total of twenty 1-min exposures, each followed by a 30 s non-emission interval. The irradiance values are presented in mW/cm² with their corresponding percentages. The highest irradiance value (10.8) was recorded at the 1st exposure at 0-mm distance (green line), representing 100% of the irradiance detected. The squares indicate the first and last exposures

Table 1 Mean and standard deviations of irradiance (mW/cm²) at different locations representing RT and LT upper central incisors, at two distances (0 and 8 mm)

Location	Irradiance (mW/cm ²)	
	0-mm	8-mm
RT	164.9 (6.1) ^{Aa}	116.3 (2.6) ^{Ab}
LT	124.3 (1.6) ^{Ba}	92.7 (15.0) ^{Bb}

Means followed by similar letters (upper case: location; lower case: within distance) are not significantly different

Irradiance with sequential exposures, simulating clinical use

The mean irradiance values during a complete whitening cycle (at the beginning and at the end of the first and last 1-min exposures) with the corresponding percentage of irradiance are displayed in Fig. 6. Regardless of the distance of the device, the irradiance dropped after the first minute of light exposure. The subsequent nineteen exposures exhibited the same behavior: the irradiance was not able to reach the initial value and continuously dropped at the end of the minute-long exposure in a spear-shaped format, even after 30 s of cooling between sequential exposures. During the last exposure, the 0-mm tip to target distance exhibited 75% (beginning) and nearly 50% (end) of initial irradiance. At the 8-mm tip-to-target distance, there was a 25% reduction in irradiance relative to that of the beginning of the first exposure and approximately a 50% reduction after the twentieth irradiation, compared to the first irradiation. Also, at all the exposures, the irradiance at 8-mm tip-to-target distance was lower than at 0-mm distance.

Table 1 depicts the values of irradiance (mW/cm²) corresponding to RT and LT. The results indicated that location (RT or LT) of the central incisors and the tip-to-target distance statistically affected the irradiance of the V-LED ($p = 0.003$). The RT central incisor received significantly higher irradiance than the LT, regardless of the distance to the light source ($p < 0.05$). The 8-mm tip to target distance promoted significantly lower irradiance for both locations (RT and LT).

Tooth color change

Table 2 displays mean/median values of color parameters (ΔL , Δa and Δb) and color change (ΔE_{00}). According to the two-way ANOVA, “staining” and “whitening protocols” statistically influenced the results ($p < 0.001$) for the color parameters of ΔE_{00} , ΔL , and Δb while the Kruskal–Wallis test detected significant differences for Δa among groups ($p < 0.001$).

Table 2 Mean and standard deviation (ΔL , Δb , and ΔE_{00}) or median values and maximum; minimum values (Δa) of color parameters for enamel stained with black tea (BT), cigarette smoke (CS), or no staining (control—CONT) when submitted to whitening with V-LED and HP gel

Whitening Protocol	CONT	BT	CS
ΔL			
V-LED	1.3 (4.5) ^{Bc}	10.3 (5.4) ^{Bb}	26.2 (9.8) ^{Aa}
HP	7.6 (2.0) ^{Ab}	26.9 (6.8) ^{Aa}	29.6 (11.7) ^{Aa}
Δa			
V-LED	0.0 (-0.1;1.1) ^{Bc}	-3.2 (-5.2; -1.4) ^{Bb}	-6.7 (-7.8; -1.3) ^{Aa}
HP	-1.6 (-2.3; -0.1) ^{Ab}	9.2 (-15.0; -1.9) ^{Aa}	-7.4 (-11.1; -3.7) ^{Aa}
Δb			
V-LED	-2.3 (1.3) ^{Bb}	-3.6 (4.3) ^{Bab}	-7.1 (3.8) ^{Ba}
HP	-6.7 (2.1) ^{Ac}	-15.7 (7.3) ^{Aa}	-11.4 (3.0) ^{Ab}
ΔE_{00}			
V-LED	2.6 (1.9) ^{Bc}	9.8 (3.7) ^{Bb}	21.0 (7.7) ^{Aa}
HP	6.0 (1.4) ^{Ab}	23.0 (6.4) ^{Aa}	23.9 (10.2) ^{Aa}

Means or medians followed by similar letters (Uppercase: whitening protocols (vertical); lowercase: staining mode (horizontal)) are not significantly different, according to two-way ANOVA and Tukey Test or Kruskal–Wallis and Mann–Whitney. Delta (Δ) refers to $T_B - T_0$; ΔL refers to luminosity differences of the L^* axis (0: black and 100: white); Δa and Δb refer to differences in the color parameters a^* (+ a^* : red; - a^* : green) or b^* (+ b^* : yellow and - b^* : blue)

HP whitening presented higher luminosity differences (ΔL) and color changes (ΔE_{00}) than whitening with V-LED on enamel unstained (CONT) or stained with BT ($p > 0.05$), but no significant differences were observed for CS-stained teeth treated with either V-LED or HP ($p = 0.508$). The HP groups presented lower color parameters (Δa , Δb) for CONT, and only this group produced higher Δb values than V-LED on CS-stained teeth ($p < 0.05$).

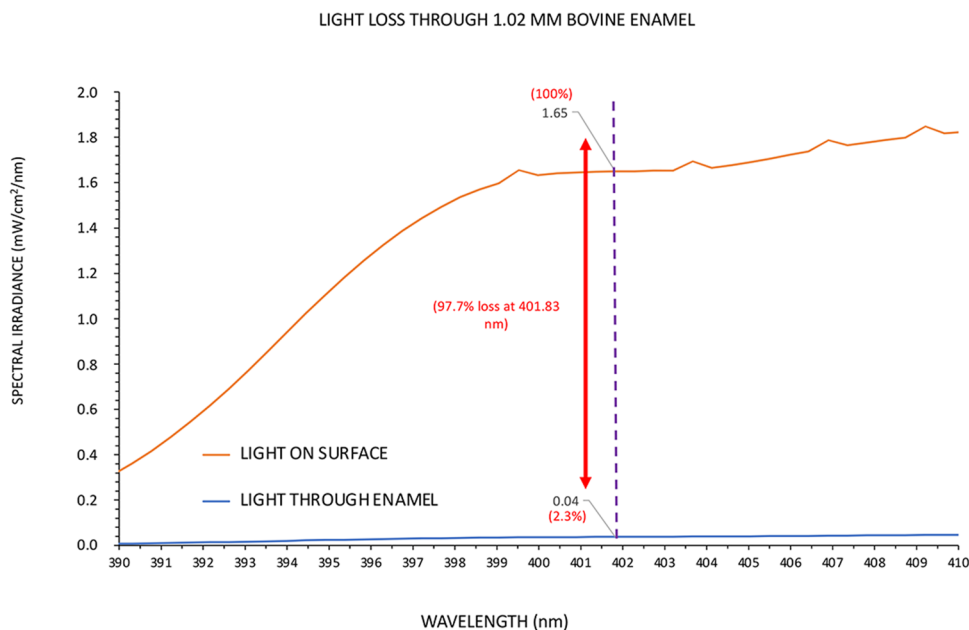
Overall, the whitening protocols produced higher color and luminosity changes (ΔE_{00} , ΔL), and lowered the color parameters (Δa , Δb) of the stained enamel (BT and CS)

compared to the unstained group (CONT). The results also showed that V-LED whitening protocol produced higher color and luminosity changes (ΔE_{00} , ΔL , Δa) on CS-stained teeth compared with the BT-stained or unstained groups ($p < 0.05$).

Light transmission through enamel

Figure 7 shows that 1-mm thick enamel attenuated approximately 98% of the emitted light at a wavelength similar to that of the V-LED light (401 nm). The open aperture of

Fig. 7 The spectral profile of the broad-banded plasma arc light. At the emission wavelength of the V-LED whitening unit (401 nm), the maximum spectral irradiance of the PAC light is seen to be 1.65 mW/cm²/nm at the enamel surface, and it is only 0.04 mW/cm²/nm after passing through the enamel specimen



the integrating sphere detected 100.0% of light transmission while the interposition of enamel detected only $2.3 \pm 0.4\%$ of the light. There was a significant reduction ($\sim 98\%$) in irradiance when the 1-mm enamel slice was interposed ($p = 0.009$). Figure 7 displays an example of irradiance detected at the specific wavelength of the V-LED light source (401 nm) on the violet line.

Discussion

The first research hypothesis was accepted, as the irradiance of the V-LED unit significantly decreased during repeated, sequential exposures. Other than distribution, irradiance was also investigated throughout the V-LED activation cycle. The spear-shaped light emission profile seen in each 1-min long light activation (Fig. 6) indicated that the V-LED source was unable to recover or maintain its irradiance during light activation in comparison to the 1st-minute values. Because LEDs generate significant thermal energy, heat dissipation technologies such as internal fans and metal heat sinks are necessary to remove heat and avoid damage to the light source [17]. Higher chip temperatures can affect the reliability of the unit by reducing the output from the LED [22]. Despite the continuous irradiance decrease during the 1 min irradiation, the 30 s interval recommended by the manufacturer for recovery did not provide enough time for the irradiance to return to its pre-rest values, probably due to incomplete chip cooling. The literature indicates that irradiance of many light-curing units is not affected in such a manner; however, the cooling down of devices is suggested among multiple uses [23], which is a limitation of the whitening V-LED because it lengthens the total exposure cycle time.

The evaluation of the V-LED device irradiance positioned at two distances away from the buccal surface of the teeth (0 and 8 mm) was determined because the manufacturer indicates that light should be 8-mm distant from the teeth. The results showed that increasing the tip-to-target distance to 8 mm resulted in a significant irradiance decrease (Table 1, Fig. 6), and as a consequence, the second hypothesis was accepted. The effects of decreasing the irradiance as the tip-to-target distance increases have been documented for dental light-curing units [17, 23]. Despite the facts that cycling cooling intervals and distance of light decreased irradiance of V-LED, these measures could attenuate pulp temperature changes. Although pulp temperature of teeth submitted to V-LED whitening has not been described, it has been demonstrated that halogen, plasma arc, and LED lights could produce in vitro temperature raise ranging from 5 to 8°C, surpassing the limit for potential pulp necrosis [17]. However, because of the low penetration of violet light through

enamel, this aspect is not considered a significant causal factor.

The findings of tooth color change (Table 2) indicated that the V-LED was able to generate perceivable color change. However, the use of the V-LED generated the same whitening effectiveness as HP whitening therapy only when applied to cigarette smoke-stained enamel. Therefore, the third research hypothesis, that the violet exposure would not significantly reach the whitening effectiveness of HP whitening gel regardless of staining type, was accepted. Previous studies verified that the V-LED light alone was able to change the color of enamel stained with black tea, but to a lesser extent than 35% HP [11, 16]. However, the present study indicated that V-LED whitening is as effective as a high-concentration of HP under cigarette-staining conditions. The more significant increase in lightness (ΔL) and decrease in redness (Δa) for cigarette smoking may indicate that the violet irradiation removed or interacted more intensely with this type of stain than with the chromophores in black tea, a solution commonly used to standardize colorimetric evaluations [26]. Thus, the present findings suggest that one type of staining may be more susceptible to violet irradiation than others. Indeed, it has been speculated that the V-LED would match the absorbance peak of staining molecules, thereby removing them from enamel by a physical process [14, 15]. Another possibility could be the deposition of smoking residuum, such as cadmium, on the enamel surface [20]. Some cadmium compounds absorb photons with energy corresponding to the violet and blue portion of the visible spectrum [21].

Light transmission through enamel revealed that 98% of violet light irradiance at the wavelength of the commercial V-LED tested was absorbed (Fig. 7). Thus, the fourth research hypothesis was accepted. For light transmission through the enamel, the plasma arc was used because it emits a broad wavelength range over the visible spectrum, including violet light [18]. Use of this type of light was necessary because of the very low levels of light passing through the 1-mm thick specimens: too low for the 6" sphere to resolve [17]. However, previous to testing, spectral irradiance peak of V-LED light source was defined at 401.82 nm, and the results showed that 1-mm thick enamel is capable of absorbing violet light irradiation in this wavelength. Although little information exists concerning violet light transmission through the enamel, literature results suggest that the irradiance of a light-curing unit emitting blue wavelengths continuously decreased as enamel thickness increased (1 to 4 mm) [19]. Even though the present study did not compare the influence of enamel thickness on the transmission of violet light, the collected data is sufficient to suggest that a thin layer of enamel is capable of absorbing (or scattering) significant levels of violet irradiation. Based on the importance

of enamel thickness to the violet light whitening, the enamel was standardized at 1-mm thick for the whiteness evaluation. The control of dentin thickness was also an important factor due to the action of HP in dentin, wherein the HP by-products would break the intrinsic pigments [4].

The beam profile images of the emitted beam from the V-LED device demonstrate high levels of non-uniformity. Even though the radiant power indicated by the manufacturer (1.2 W) [16, 26] was confirmed, the beam-profile images, both in 2-D and 3-D profiles, demonstrated the non-homogeneous distribution of irradiance across the tip of the light. Although the irradiance considers the area of the surface receiving the light, it only provides information of an average output [17], and it does not indicate the presence of areas with higher or lower irradiance, known as locations with “warm” or “cold” colors, respectively [18]. The measurement of the irradiance set at the RT and LT central incisors confirmed an irregular distribution of irradiance. To date, there are no reports in the literature of beam profile analysis in light sources used for in-office tooth whitening. The clinical implications of these local irradiance values can be of importance. If the intensity of light is a causative factor in the effectiveness of violet light to whiten a stain, then one might expect a non-uniform stain removal, if the light itself demonstrated a highly nonuniform spatial output.

The present study findings suggest that color change resulting from exposure to the V-LED alone may be clinically perceptible, because ΔE_{00} was higher than 0.8 in all groups: the minimal color change value that is visually detectable [29]. These data corroborate findings from other authors that also observed perceivable color change due to exposure to a V-LED alone [11, 16]. More pronounced whitening for stained enamel could corroborate the assumption that violet light matches with absorbance peak of various pigment types [13, 15, 30]. Thus, a clinical discoloration caused by cigarette smoke could benefit from application of this protocol. It is important to notice that the simulated protocol of cigarette smoke staining was based on a standard frequency of smokers, previously determined in another study [28]. Because previous research demonstrated that cigarette smoking deposits chemicals (nickel, cadmium, and lead) on enamel surfaces [20], which could absorb violet wavelength energy [21], the behavior of violet LED whitening on this type of substrate is crucial for understanding the role of this novel technology in smokers. Also, because a randomized clinical trial pointed out that whitening with CP was stable in smoker patients after 12 months only following dental prophylaxis [31], alternative treatments for this type of staining could contribute to the whitening effectiveness in smokers. On the other hand, black tea staining was elected to evaluate the effect of violet light in at least two types of pigments, with the tea, in particular, simulating a dietary habit that enables the deposition of polyphenolic molecules

instead [7]. Black tea staining for 24 h is sufficient to attain high levels of darkening before whitening procedures, being a commonly used protocol in studies evaluating the effectiveness of tooth whitening products [11, 16].

Also, results showed that the violet wavelength demonstrates low capacity to diffuse through the enamel. Indeed, violet light was unable to pass through 1-mm thick enamel samples. Therefore, data indicates that the V-LED effect is probably only superficial, and light would possibly interact or cleave only extrinsic, surface pigments. In contrast, due to the known trans-dentinal hydrogen peroxide diffusion ability [4], it is expected that free radicals released by hydrogen peroxide will be more dynamic in removing pigments in deeper enamel and dentin structures. The data from the present study corroborate the findings of a randomized clinical trial, where non-smoking volunteers submitted to whitening only with a V-LED light presented a lesser whitening outcome than those treated with high-concentrated whitening gels [13]. The fact that the V-LED treatment (up to 10 sessions) is longer, along with the lower whitening effect compared to HP (up to 2 sessions), also represent a major drawback of V-LED technique.

Characteristics of the V-LED device also provided important information that could be extrapolated into clinical conditions. Firstly, the irregular distribution of the beam profile raises the concern that light irradiance would heterogeneously reach the surface of the teeth, thereby promoting irregular interaction of the light with the staining along the teeth. In this sense, the evaluation of beam profile using a ground glass target, which could work as a “homogenizer,” provided important information suggesting that irradiance could be more regularly distributed if a homogenizer tip was used, which is in accordance to recent concepts developed for dental light-curing units [24]. Secondly, the length of the exposures and intervals cycle seems to affect the stabilization of the V-LED emission levels. However, the decrease of exposures and increase of interval time could affect the whitening outcomes as well as extend the number of sessions required for treatment, which is already a drawback of the V-LED protocol in comparison to the HP whitening protocol [16]. Finally, even though the manufacturer-recommended 8-mm distance to not overheat the pulp, the tip-to-target distance diminished the irradiance of the V-LED light. Perhaps this distance was also suggested to not significantly affect gingival tissues, which would also be in the V-LED path during exposures.

A limitation of this study was the color change evaluation, as staining in an in vitro condition is exacerbated in comparison to a clinical situation. Also, a staining depth evaluation along with light transmission could have determined the extent of the V-LED action on enamel color change. Pulp temperature evaluation could have addressed the necessity, or not, of increasing the device’s distance from

the teeth, as clinical trials have already demonstrated that tooth sensitivity is observed with V-LED whitening protocols [9, 13]. Therefore, further investigations about the effect of pulp temperature variation should be conducted in order to provide information on the safety of V-LED use on patients. Further research could also improve the light emission stability and uniformity of the devices in order to ensure the quality of the whitening protocol.

Conclusions

Within the limitations imposed by the methodology used in this study, the following conclusions can be drawn:

- 1) The irradiance of the V-LED was negatively affected by the repeated sequential exposures and intervals and the 8-mm tip distance,
- 2) Even though V-LED exposure alone was able to produce a perceptible color change, it presented similar results to HP only when enamel was stained with cigarette smoke, and
- 3) About 98% of the V-LED light was not transmitted through 1-mm enamel.

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Declarations

Ethics approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to participate For this type of study, formal consent is not required.

Conflict of interest The authors declare no competing interests.

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