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Original Article

Effect of various post-curing light intensities, times, and energy levels on the color of 3D-printed resin crowns

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Abstract *Background/purpose:* Current 3D-printing technology has been widely used for creating dental resin restorations. This study aimed to evaluate the effect of light intensity, time, and energy post-curing on the surface color of 3D-printed resin crowns. However, the influences of post-curing parameters on the restoration after printing still need to be explored. Therefore, this project investigates the effect of post-cure conditions on resin color.
Materials and methods: Specimens from single-crown (SC) and pontic (PO) specimens underwent post-curing at various light intensities (105, 210, 420, 630, and 860 mW/cm2) for 5, 10, and 15 min. Specimens were observed at three predetermined points and measured using a commercial spectrophotometer that utilizes the CIE Lab* color space. Subsequently, samples were analyzed for color differences (ΔE).
Results: ΔE color differences in evaluated samples were influenced by the light intensity, time, and energy post-curing. SC samples showed a significant color difference ($P < 0.05$), with the lowest value at 5 min of 16 (860 mW/cm^2), while 10 and 15 min had a difference of 4 (210 mW/cm^2). PO samples exhibited a significant decrease in the color difference ($P < 0.05$) at 5 and 10 min of 16 (860 mW/cm^2), and at 15 min of 12 (630 mW/cm^2).

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Conclusion: The results of this study indicate that exposing a resin crown to a high light intensity results in color stability and allows shorter post-curing times.

Introduction

With advancements in technology, people's perceptions and demands for dental aesthetics have gradually increased.[1,2] Therefore, producing restorations that closely resemble a patient's natural teeth is essential. Recently, three-dimensional (3D) printing technology has resulted in breakthroughs in most medical and dental fields,[3] with the development of computer-aided design/computer-aided manufacturing (CAD/CAM).[4] Dental CAD software is utilized for design, followed by subtractive (milling) or additive (3D-printing) processes.[5] At present, there are many types of 3D printing machines, among which liquid-crystal display (LCD) printers are widely used in dental clinics due to their advantages in terms of price and convenience.[6] Moreover, color tones of 3D-printed resins vary significantly among commercially accessible items. Numerous variations in qualitatively identified color dimensions have been uncovered. In contrast, color tones fluctuate due to the presence of various aspects during the 3D-printing process.[7]

3D-printing technology is used in dental clinics to create diagnostic models, complete dentures, temporary restoratives, occlusal splints, and surgical guides. Its use is also developing in dental restorations.[4] Dental prostheses and restorations produced with 3D technology can be precisely made.[8] This technology provides dentists and patients with time-saving benefits because of its rapid processing times, mainly when utilized as a fixed prosthodontic or temporary material.[9] However, 3D-printing results can be directly affected by material selection, printing orientation, and post-processing procedures.[10,11] The intended use of the final product determines the selection of 3D-printing materials in the dental field. Polymer-based materials are widely used to manufacture dental crowns using additive technology.[12] Color changes of 3D-printing resins with curing times are mainly due to the photoinitiator. The right combination of photoinitiator and co-initiator and a suitable exposure time to the light source can increase the mechanical strength.[13] Shin et al. reported that the color stability differed between two types of 3D-printing resins due to differences in resin compositions.[14] Therefore, further studies on the color stability of 3D-printing resins according to post-curing treatment parameters, such as the ideal light source or time, are needed.

Post-curing aims to enhance the mechanical properties of the printed prosthesis, and increasing the post-cure time can effectively reduce color changes of the resin.[15] Alshamrani et al. indicated that various parameters should be controlled to obtain optimal 3D-printing results. These parameters include the build angle and position, layer thickness, and the method of post-polymerization.[16,17] In addition, Scherer et al. showed that the properties and accuracy are influence by the post-polymerization time.[18] The depth of light polymerization may differ for each polymer due to compositional differences in viscosity, the photoinitiator, pigments, and the light source strength of the selected 3D-printer. Nevertheless, no research has explained whether there is a post-polymerization relationship of power to color changes. Another factor that affects the polymerization of 3D-printed objects is the total energy absorbed during the polymerization process. The total energy (in mW/cm^2) is determined by combining the transmitted light intensity (mW/cm^2) with the curing time (min). The total exposure energy has a significant influence on the mechanical performance.[19]

Therefore, this study aimed to evaluate the effects of light intensity, time, and energy post curing on the surface color of 3D-printed resin crowns. The null hypothesis was that the color of 3D-printed resins would not be affected by differences in the light intensity or time. It was expected that color changes of crowns could be regulated through variations in the irradiation energy.

Materials and methods

Using CAD software (inLab WS16, Dentsply Sirona, North Carolina State, NC, USA), the SC and PO specimens were designed. The models were then saved in standard tessellation language (STL) and exported to 3D-printing slicing software (Alpha 3D 3.0.3, Ackuretta, Taipei, Taiwan). Specimens were then printed using a liquid-crystal display (LCD) type printer (Veribuild, Whip mix, Louisville, KY, USA) with a layer thickness set to 50 μm, illumination time of 12 s, and a base layer of four for all prints. The 3D-printed crown and bridge material type with A2 color was used in this study (Printin, Printin3D, Taoyuan, Taiwan). According to the information provided by the manufacturer, the 3D printing materials are mainly composed of urethane acrylate 30—40%, acrylic monomer 55%—65%, 1.6-hexanediol diacrylate 5%—15% and photoinitiator 0%—5%. After printing, specimens were rinsed twice in 90% isopropanol and cleaned in an ultrasonic machine (EASY Series, Elma, Singen, Germany) for 5 min to remove excess material.

Specimens were post-cured in an ultraviolet (UV) light polymerization chamber (Printin3D) using a 405-nm light source consisting of 12 multidirectional light-emitting diodes. Each specimen underwent post-curing at light intensities of 105, 210, 420, 630, and 860 mW/cm^2 for 5, 10, and 15 min. The specimens were divided into two groups: SC and PO, each comprising three replicates ($n = 45$ in each group; $N = 90$ in total, Fig. 1).

This study aimed to assess the color differences of post-cured specimens within each experimental group,

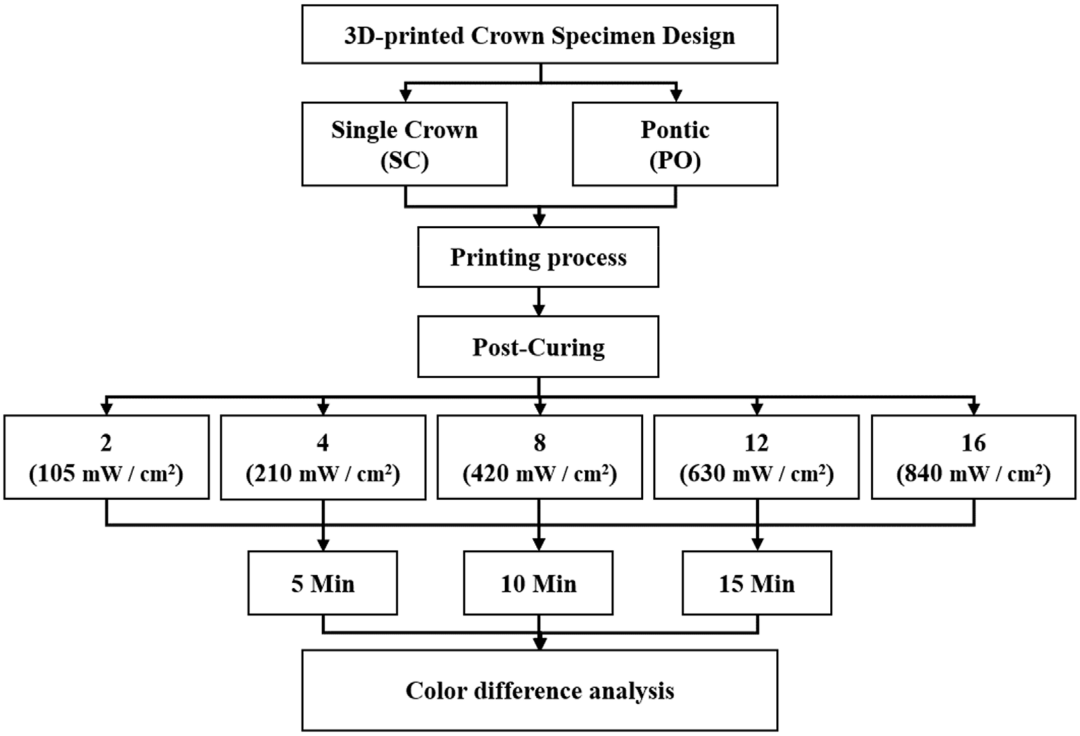

Figure 1 Flowchart of the overall experimental process of this study.

employing varying light intensities, times, and energy levels. Specimens were analyzed at three predetermined points (as shown in Fig. 2) and measured using a commercial spectrophotometer (VITA Easyshade®, VITA, Bad Säckingen, Germany). Samples were positioned on a standard black baseplate background,[20] and color measurements were conducted using VITA A2 colors ($L* = 75.74$, $a* = 1.79$, $b* = 18.05$) in the CIE Lab∗ color model developed by the International Commission on Illumination (CIE). This model allows for the precise determination of resin color differences (ΔE) within a 3D context[21] The a∗ and b∗ axes in the CIE Lab∗ color model are oriented at right angles to each other and represent the color dimensions of a specimen (a∗ represents the ratio of red to green, and b∗ represents the ratio of yellow to blue).[22,23] The third axis, L∗, is perpendicular to the a∗ and b∗ planes and represents lightness.[24,25] Specimens were post-cured by a single operator at 5, 10, or 15 min intervals. Color differences were then calculated using the following formula:[26]

$$\text{Color difference } (\Delta E) = \sqrt{(L^{*1} - L^{*2})^2 + (a^{*1} - a^{*2})^2 + (b^{*1} - b^{*1})^2}$$

Data are expressed as the mean ± standard deviation (SD) of the four replicate samples and were analyzed using JMP 16 software (Statistics Analysis System, North Carolina State, NC, USA). A one-way analysis of variance (ANOVA) followed by Tukey's honest significant difference (HSD) post-hoc test was used to determine the significance level. $P < 0.05$ was considered a significant level.

Results

Fig. 3 displays color measurement results obtained using two distinct color parameters for the cusp, median, and marginal surfaces. The CIELAB color coordinate values (a∗ and b∗) revealed differences for each surface examined. In Fig. 3a, the median buccal surface presented the lowest value for a∗, of 0.11 ± 0.01, while the marginal buccal surface showed the lowest value for b∗ of 14.20 ± 1.73.

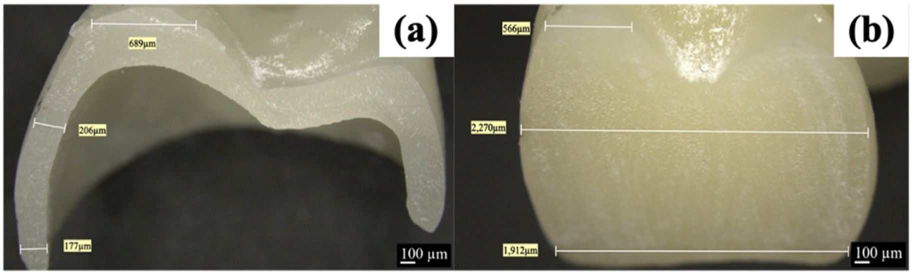

Figure 2 Illustration of the measurement color landmarks of the single crown (a) and a pontic (b).

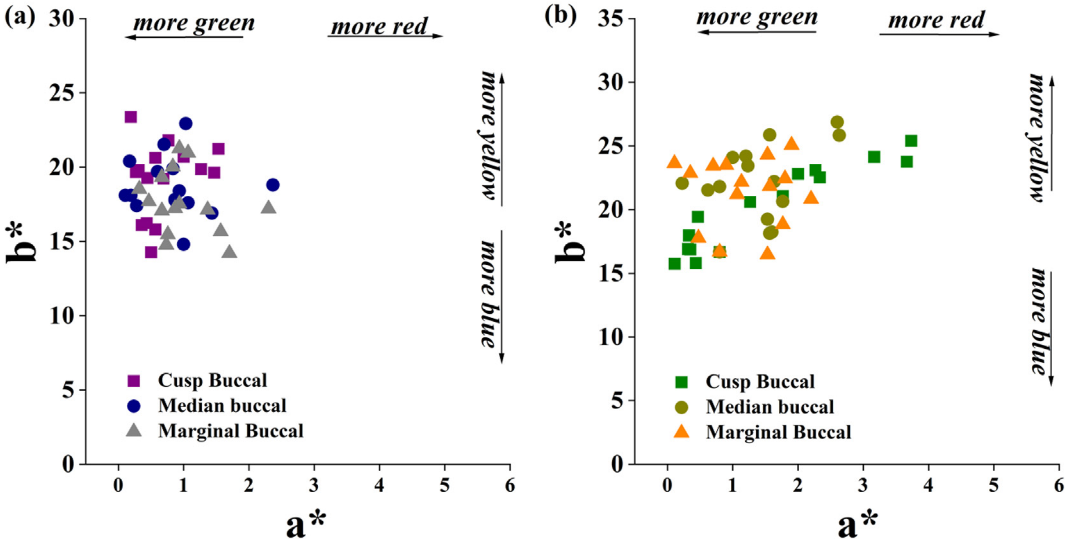

Figure 3 Graphs displaying CIELAB color coordinates for the single crown (a) and a pontic (b).

Conversely, Fig. 3b demonstrates that the buccal cusp surface presented the lowest values for both a$*$ and b$*$ with respective values of 0.11 ± 0.01 and 15.73 ± 0.49.

The mean color difference (ΔE) was measured and compared among different study groups. In Fig. 4a, depicting a single crown test sample, a significant color difference can be observed on the cusp and marginal buccal regions when exposed to light intensities above 8 (420 mW/cm^2) for 5 min ($P < 0.05$). The optimal light intensity observed was 16 (860 mW/cm^2) with 5-min exposure. However, when the exposure time was extended to 10 and 15 min, it was found that a light intensity of 210 mW/cm^2 yielded lower value results. Furthermore, when comparing light intensities at 5 and 10 min, no significant difference was found, unlike at the 10 min, where a significant difference ($P < 0.05$) was observed with a light intensity of 4 (210 mW/cm^2). Contrasting results were observed in Fig. 4b at 5 and 10 min, where significant decreases in color difference values were observed at all three test points ($P < 0.05$) when exposed to a light intensity of 4 (210 mW/cm^2). The decrease in value continued with an increasing light intensity. However, when the exposure time was

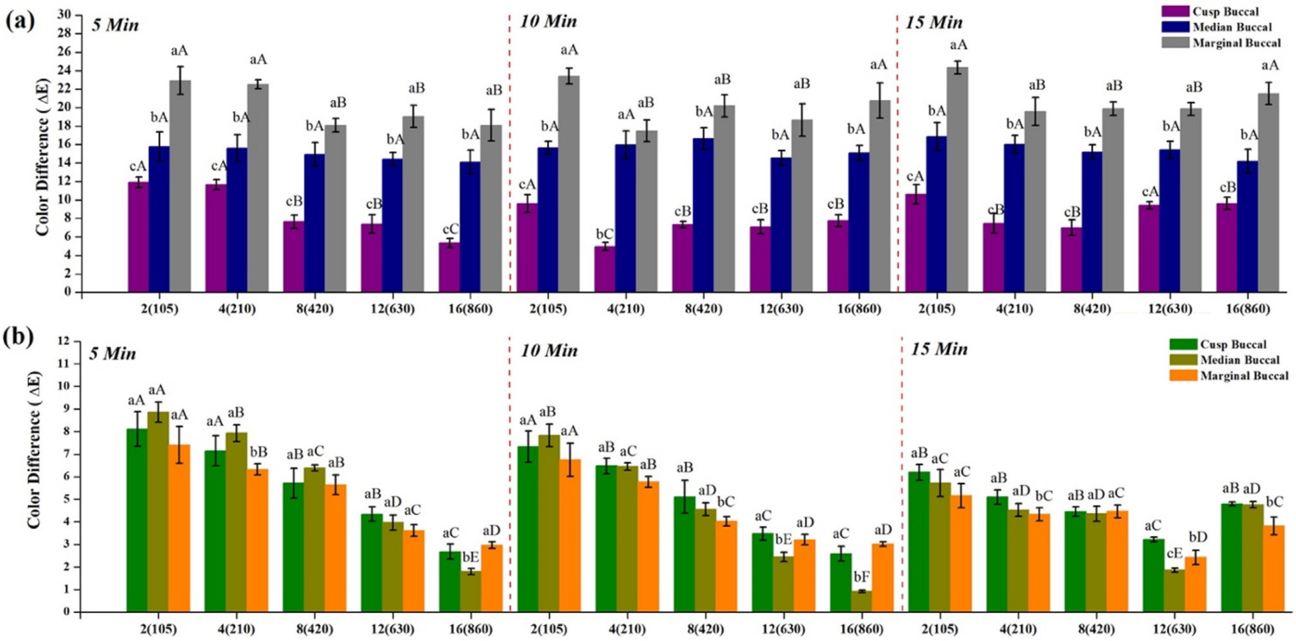

Figure 4 Graph showing variations in color tones based on differences in light intensity and time for the single crown (a) and a pontic (b). Means with different letters were significantly different ($P < 0.05$, mean ± SD, n = 10). Capital letters represent comparisons of different light intensities at fixed times. Lowercase letters represent comparisons of different positions at a fixed time and energy conditions.

Table 1 The total energy of post-curing after 3D printing.

Code name	Light intensity	5 min	10 min	15 min
2 (105)	2 (105 mW/cm^2)	525	1050	1575
4 (210)	4 (210 mW/cm^2)	1050	2100	3150
8 (420)	8 (420 mW/cm^2)	2100	4200	6300
12 (630)	12 (630 mW/cm^2)	3150	6300	9450
16 (860)	16 (860 mW/cm^2)	4300	8600	12,900

Light intensity: the unit of energy is mW/cm^2.

extended to 15 min, no significant difference was observed, except for a light intensity of 12 (630 mW/cm^2), which resulted in a significant difference in the color difference value ($P < 0.05$).

Results of the exposure to light energy, along with the corresponding calculation results, are presented in Table 1. In Fig. 5a, the lowest color difference is depicted, which was considered acceptable only on the buccal cusp surface with a value of 5.35 ± 0.47, corresponding to an energy supply of 4300 mW/cm^2. In contrast, Fig. 5b demonstrates that all buccal surfaces in the pontic test group exhibited acceptable values of color difference.

Discussion

Provisional restorations are commonly utilized for functional and aesthetic diagnostic purposes.[27] Dentists employ them to provide patients with a preview of the final treatment, thereby boosting the patient's confidence in the procedure, especially in color matching.[28] In this study, the colors of crowns and pontic bridges were evaluated and compared. Results revealed that colors varied among samples and changed depending on the light intensity and the post-curing time period. Consequently, the null hypothesis, which suggested that differences in light intensities and times would significantly affect the surface color of the 3D-printed resin crown, was accepted. While several studies explored the effect of differences in post-curing times on color differences,[4,5] none evaluated the combined impact of time and light intensity. In this regard, findings of this study are expected to contribute to existing knowledge by determining the appropriate intensity and time required to achieve different colors with minimal discoloration when creating 3D-printed crowns.

Based on data presented in Fig. 3a and b, results indicate that the median buccal surface tended to show colors that are green and blue, as evidenced by the lowest a∗ and b∗ values compared to the other surfaces. In contrast, the cusp and marginal surfaces did not show significant color variations, with colors tending to be green and yellow. The observed color differences between the surfaces can be attributed to various factors, such as variations in enamel thickness, degree of mineralization, and the presence of stains or discolorations.[29] An increase in the color change was found with a decreasing enamel thickness.[30] In contrast, the thicker enamel on the cusp and marginal surfaces may cause light to be reflected differently, resulting in more-consistent green and yellow colors.[31] The threshold criteria adopted in this study for evaluating color differences were ΔE ≥ 2.6 and ≤ 5.5. These criteria were primarily utilized to assess the magnitude of color

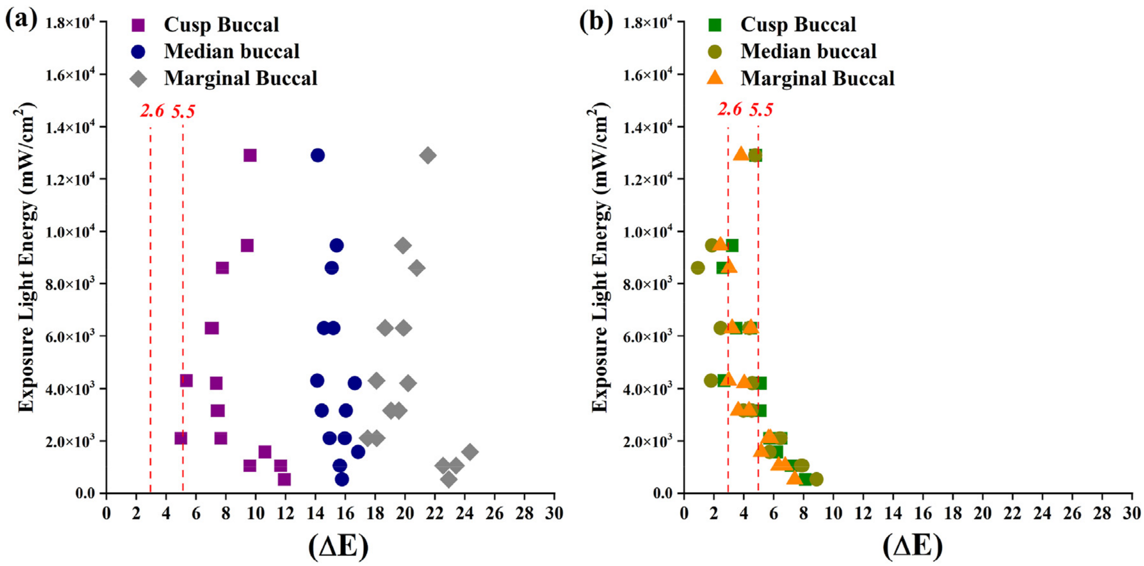

Figure 5 Graphs displaying the exposure light energy for the single crown (a) and a pontic (b).

variations.[32] A citation from the web of science also recommends $\Delta E \geq 3.7$.[33] Due to an ongoing controversy surrounding the gold standard threshold value, further investigation is required to determine clinically discernible color differences that more accurately reflect real-world clinical scenarios. This suggests the necessity for additional research in order to establish a threshold value that aligns with practical clinical situations.

Results showed that the choice of light intensity and exposure time had major effects on color changes. In the single-crown test sample (Fig. 4a), exposure to a light intensity above 8 (420 mW/cm^2) for 5 min resulted in a significant color difference in the cusp and marginal buccal areas. This suggests that lower light intensities can lead to greater polymerization and potentially lead to higher levels of discolouration in these areas. The optimal light intensity was found to be 16 (at 860 mW/cm^2) with 5 min of exposure, indicating a threshold beyond which excessive light intensity cannot further improve color stability. Interestingly, when the exposure time was extended to 10 and 15 min, a lower light intensity of 4 (210 mW/cm^2) gave the best results. These results are in agreement with a study conducted by Montero et al., which concluded that 5 and 10 min post-curing period would lead to an acceptable change in material color.[34] This indicates that prolonged exposure allows sufficient polymerization even at lower light intensities, resulting in reduced discoloration. It makes sense that a longer exposure time compensates for a lower energy supply, ensuring adequate preservation and color stability. However, the mechanisms underlying this phenomenon require further investigation. Comparing the color changes at 5 and 10 min showed no significant difference when using various light intensities. This suggests that an initial exposure time of 5 min may be sufficient to achieve optimal color stability. However, a significant difference occurs at a light intensity of 12 (630 mW/cm^2) at 10 min. This implies that extended exposure beyond the initial 5 min can have a color-stabilizing effect, so low light intensities can be used. Therefore, when time is a critical factor for completing a restoration, increasing the light intensity can reduce the required irradiation time while still obtaining similar optimization results. This study was limited to examining color changes of resin restorative materials. In the future, we will continue to explore the impacts of post-processing energy on the strength and accuracy.

Fig. 4b presents contrasting results, showing a significant decrease in the color difference with an increasing light intensity at 5 and 10 min. This suggests that higher light intensities may contribute to increased color stability at this specific test point. However, no significant difference was observed when the exposure time was extended to 15 min except for a light intensity of 12 (630 mW/cm^2). These findings suggest that the energy supply and surface area being treated play critical roles in the degree of color change observed. This finding has significant implications for clinicians, emphasizing the need for careful consideration of energy levels to achieve optimal results in color-matching procedures.

Changing the time will affect the rate of polymerization.[35] In previous studies, various factors that could potentially affect color stability were evaluated. For instance, the anatomical shape of the buccal region was examined as it may influence the accessibility of light and the degree of polymerization.[34] Additionally, variations in irradiance were observed across different sections, further contributing to potential impacts on color stability. The effect of location on the polymerization plate also affects the color. The color tone can also vary depending on the concentration of the photoinitiator. A higher concentration of photoinitiator will result in increased absorption of light energy, leading to a significant impact on the manifestation of color.[5] The present study demonstrated a significant correlation between the thickness of the 3D-printed crown and the resulting color change. Specifically, when comparing the SC sample, with a thinner thickness than the pontic. It exhibited a notably higher color difference value. These findings are consistent with research conducted by Bayindir et al., who reported a substantial increase in color difference values accompanying a decrease in crown thickness.[36] However, further research is necessary to explore differences in thickness across various dimensions.

Within the scope of this study, it was concluded that different light intensities and post-curing times had an influence on the color of 3D-printed resin crowns. Exposure of a resin crown to a high light intensity with a short post-curing time resulted in color stability. A light intensity of 16 (860 mW/cm^2) for a duration of 5 min was found to be acceptable. Moreover, to achieve this desirable color difference, an optimal additional energy level of 4000—8000 mW/cm^2 is required.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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